Phase-2 Upgrades of CMS

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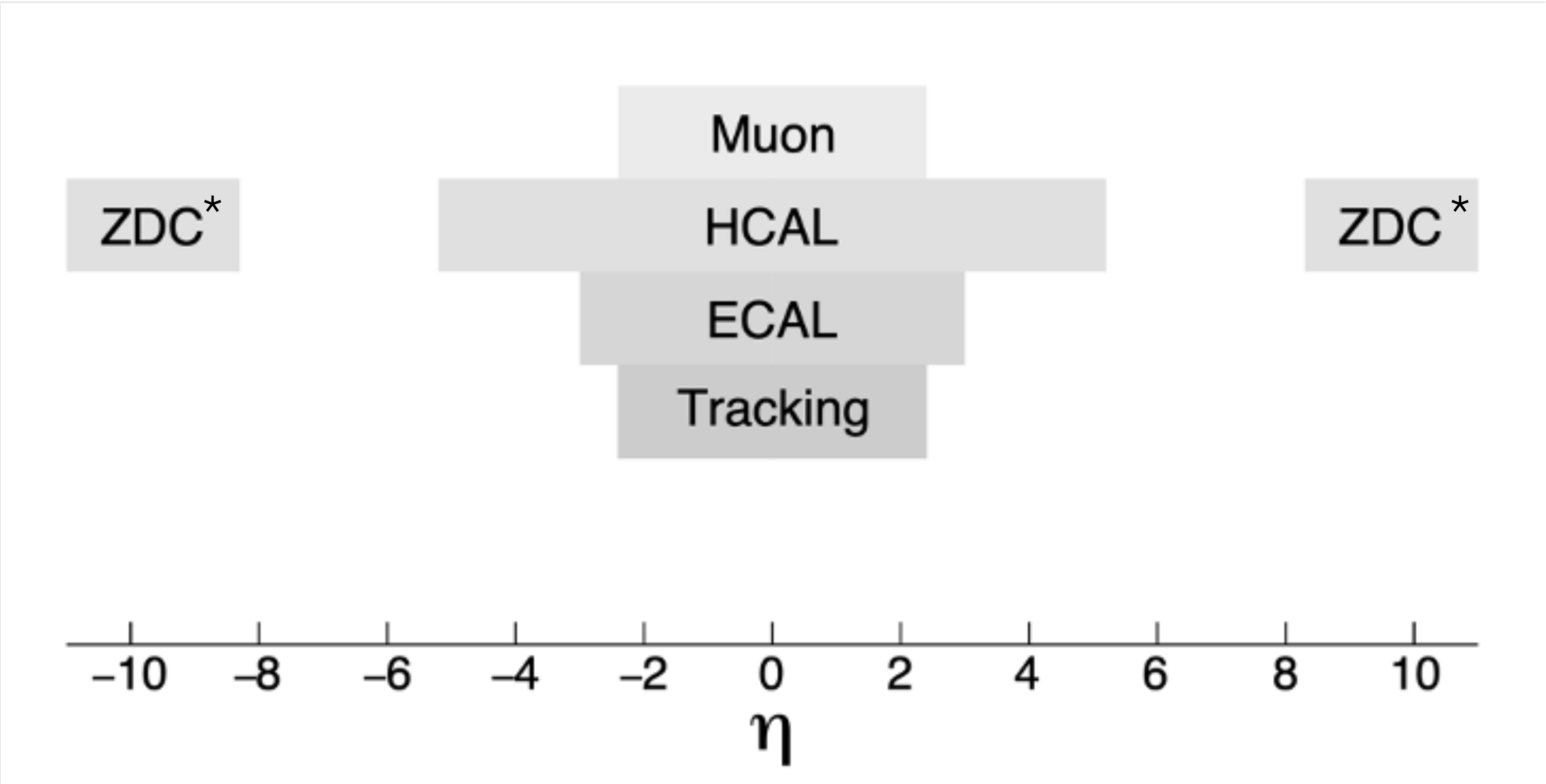
LLR — École Polytechnique

“Synergies between the EIC & the LHC”

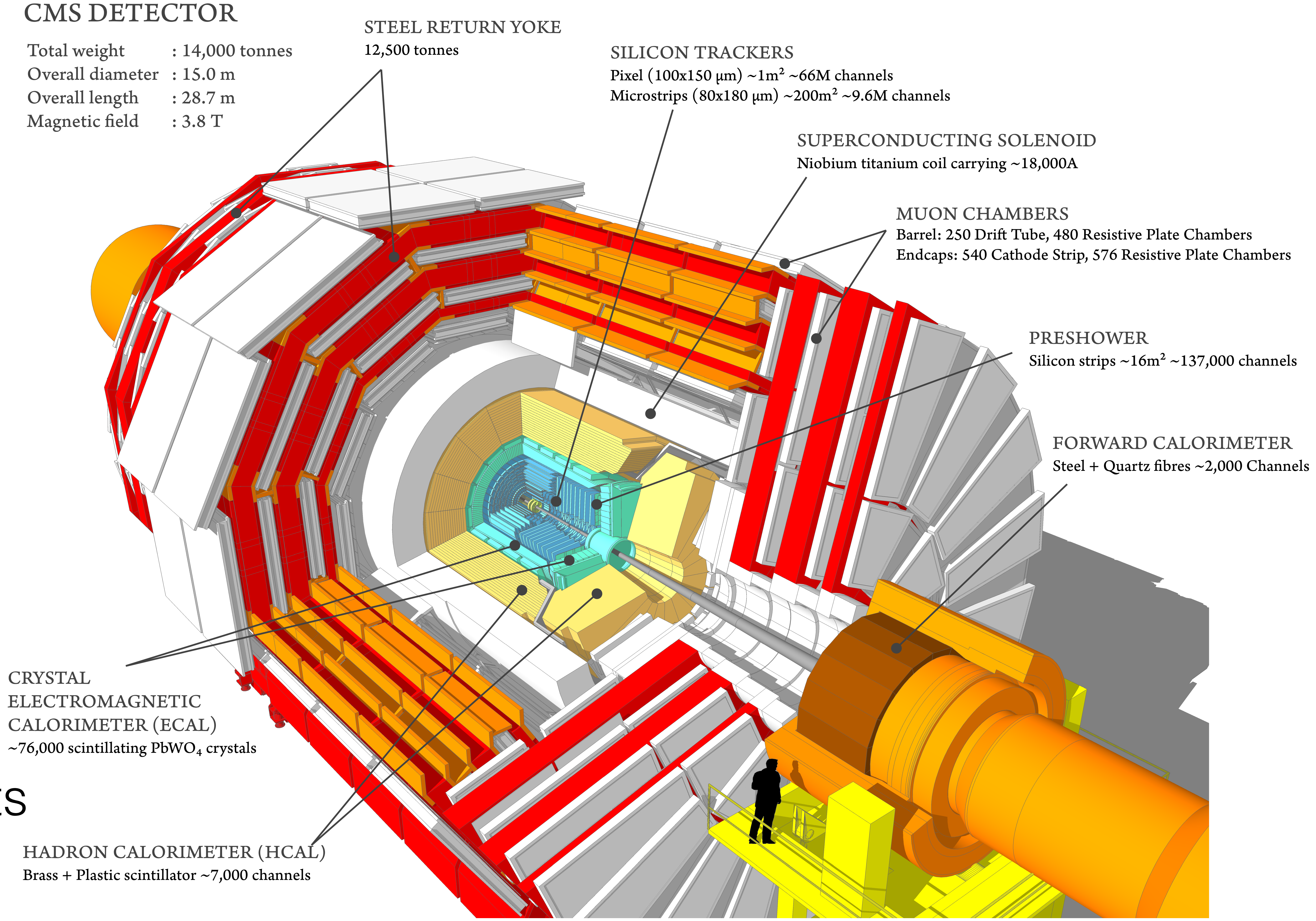
September 23rd, 2025

The CMS detector today: "Phase 1"

Full coverage tracking, calorimetry & leptons in $|\eta| < 2.5$
High B-field for excellent track p resolution



*Not available for all collision systems

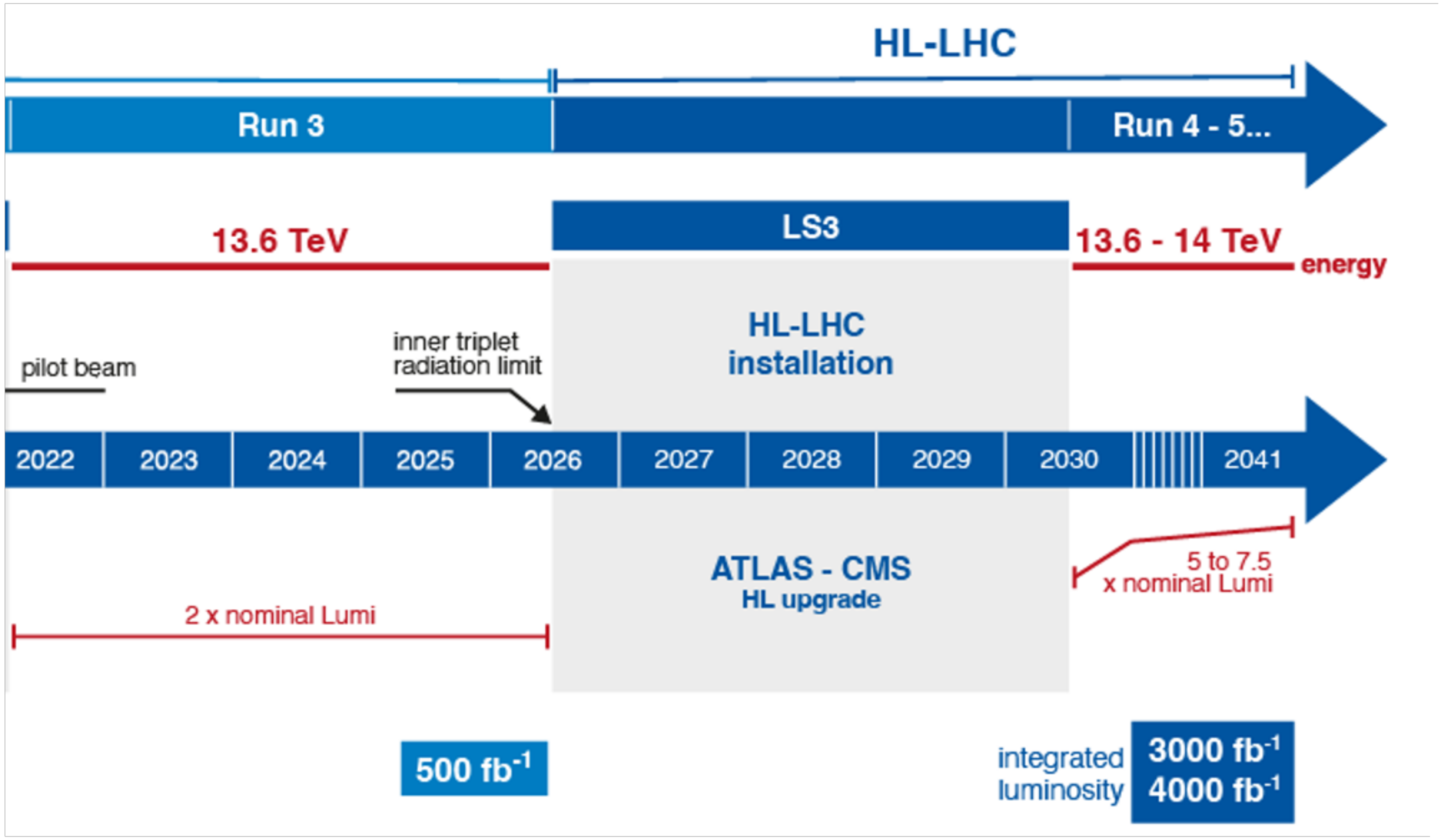


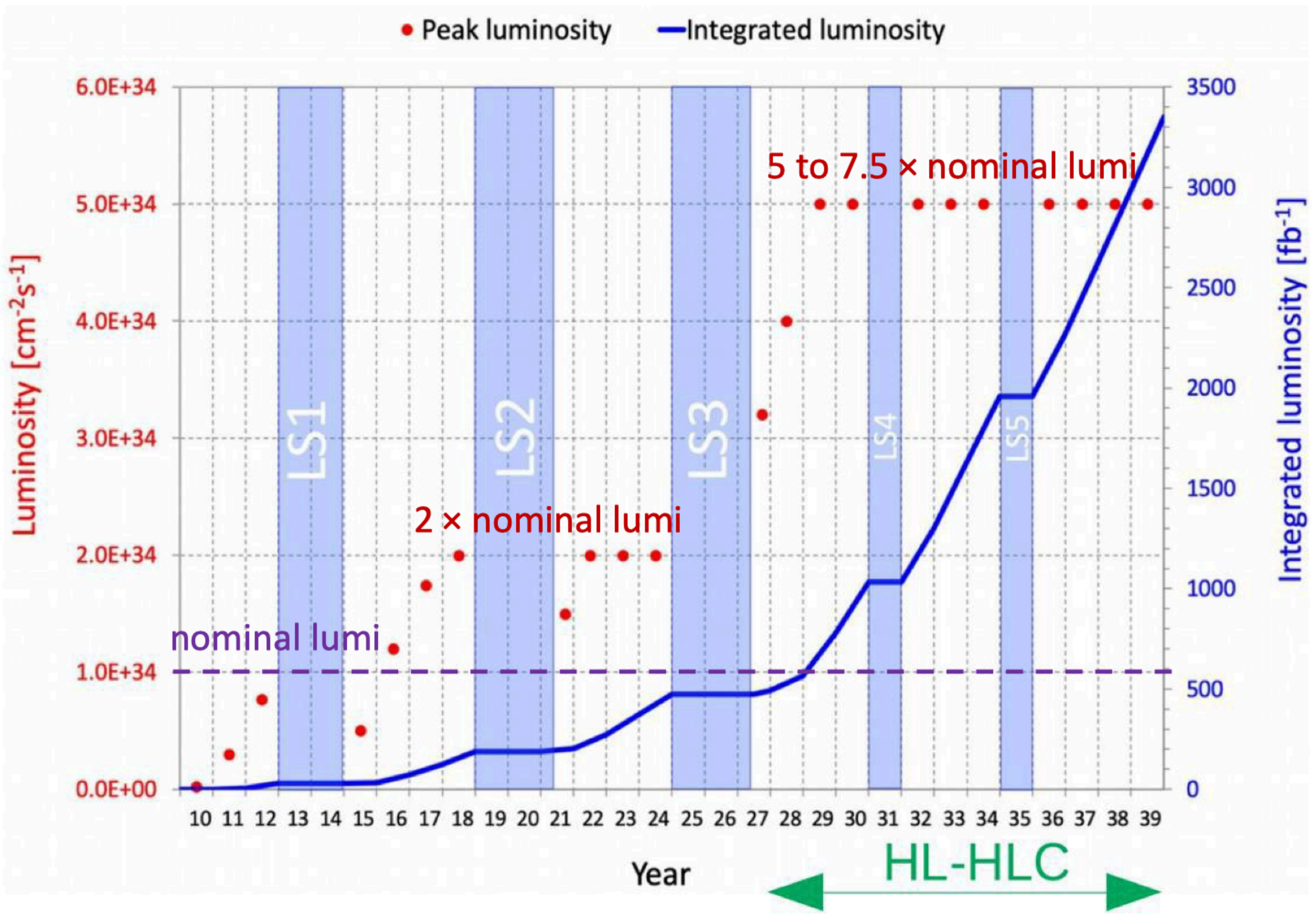
High rate capability for triggering on rare events

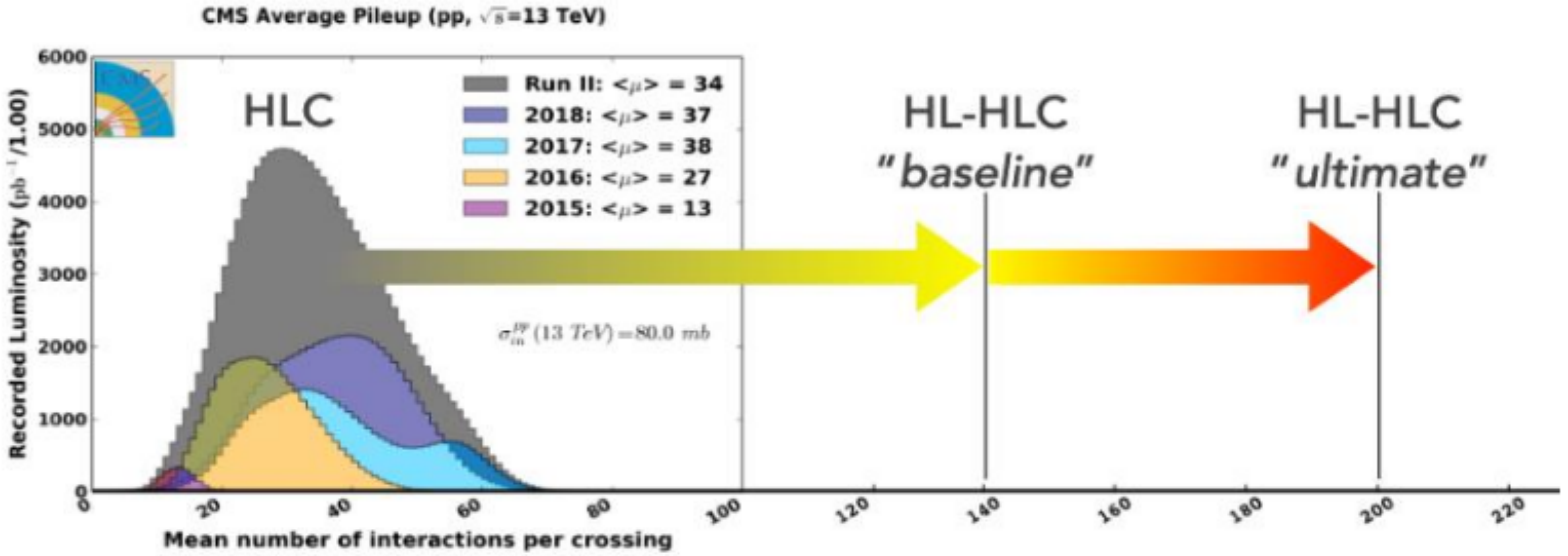
- Bunch crossing rate: 40 MHz (up to 60 PU)
- L1 accept rate: 100 kHz
- Typical HLT bandwidth: 1kHz

High Luminosity LHC

Accelerator upgrades increase instantaneous luminosity several-fold
Integrated luminosity will increase by nearly an order of magnitude







Requires a completely new version of CMS:

- Replacement of detectors & electronics already near max. dose w/ rad-hard technologies
- Detectors and reconstruction that is optimized for 140 — 200 simultaneous interactions

Phase 2 upgrades

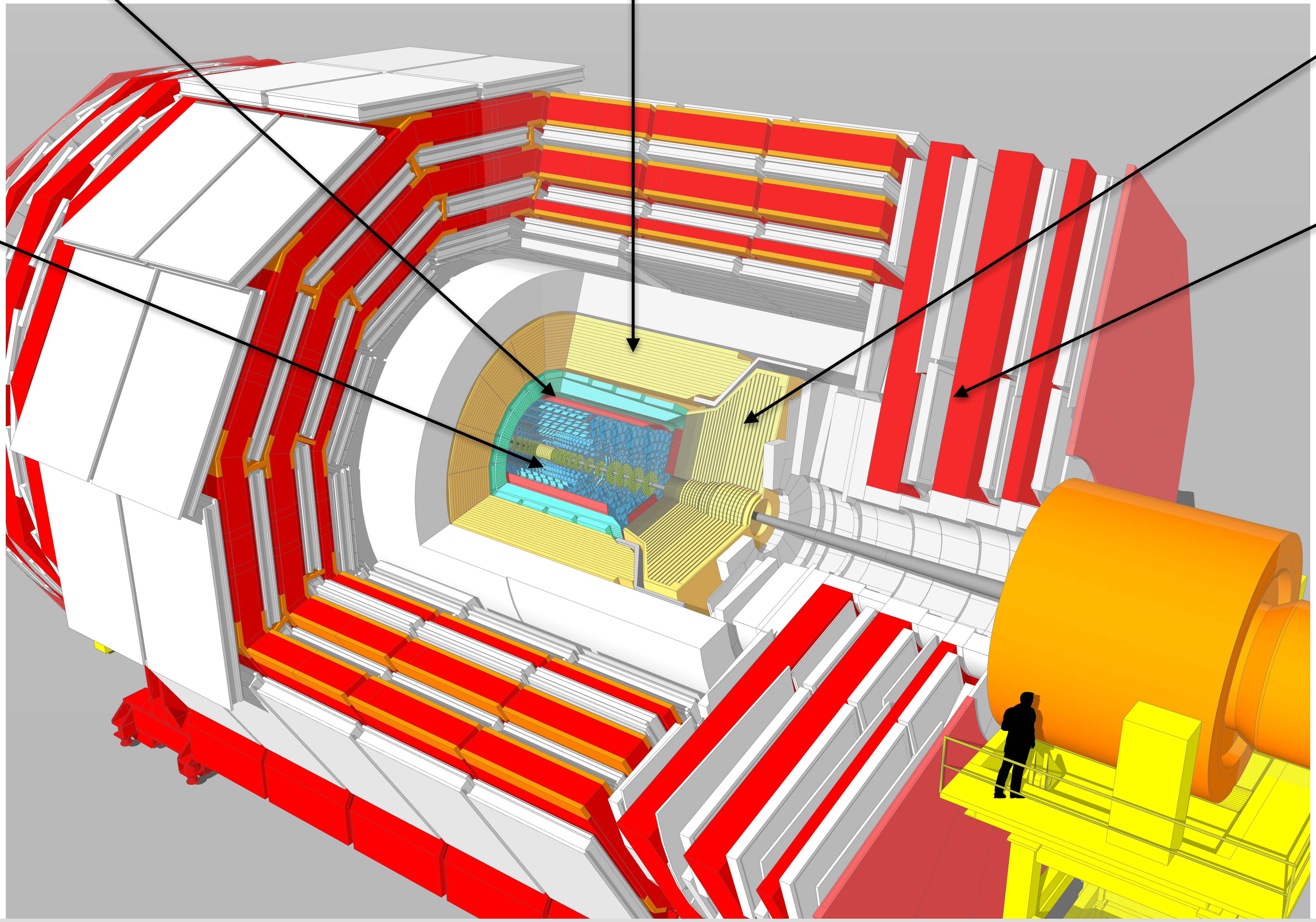
MIP Timing Detectors
Pile-up rejection
PID via TOF (π/K/p)
$|\eta| < 3$

Barrel Calorimeters
New electronics
Colder ECAL operation

Calorimeter endcap
Novel high granularity device
Designed for particle flow

Tracker
Rad-hard & thin
$|\eta| < 2.4 \rightarrow |\eta| < 3.8$

Muon Detectors
New GEM & iRPC
$|\eta| < 2.4 \rightarrow |\eta| < 2.8$



DAQ / High-Level Trigger
1 kHz → 7.5 kHZ

L1-Trigger
Includes tracking
100 kHz → 750 kHZ

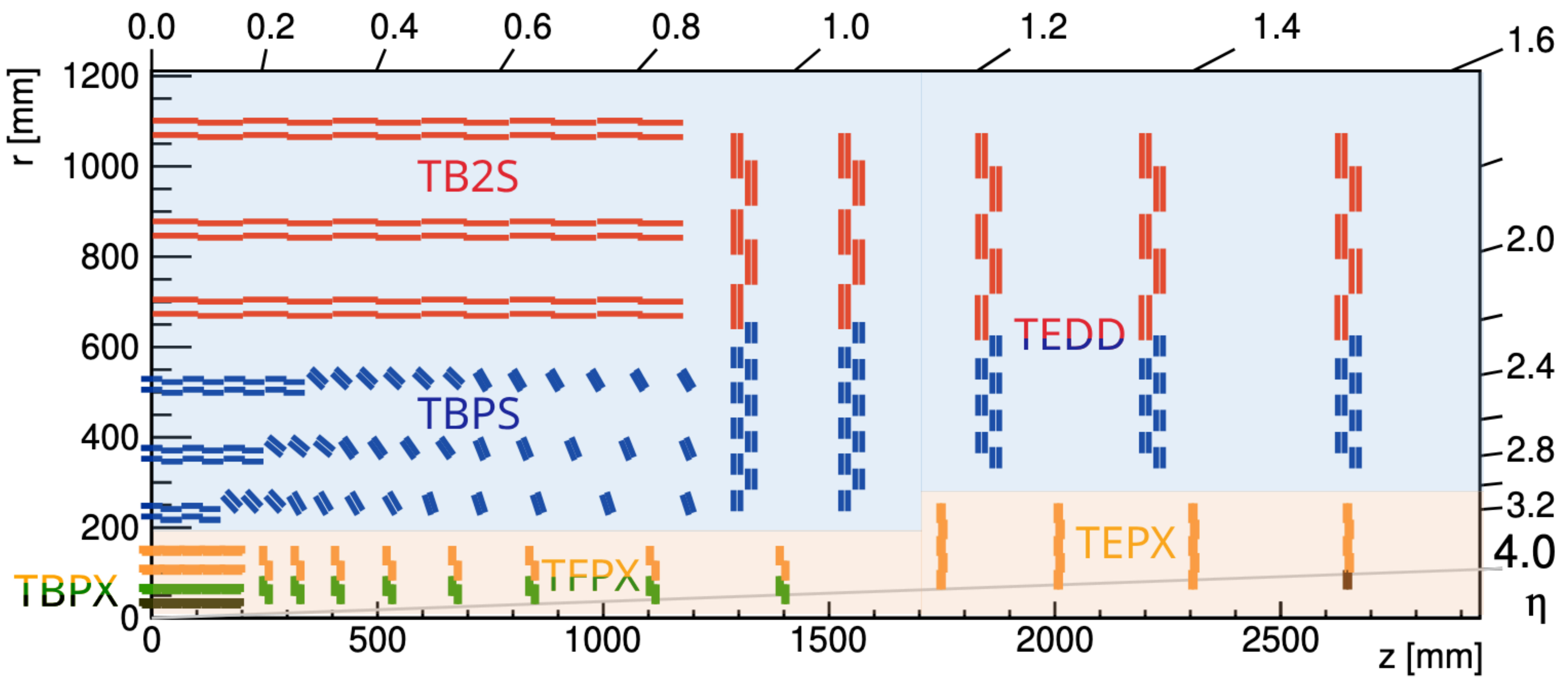
Beam Monitoring & Luminosity
Bunch-by-bunch luminosity:
2% online, 1% offline

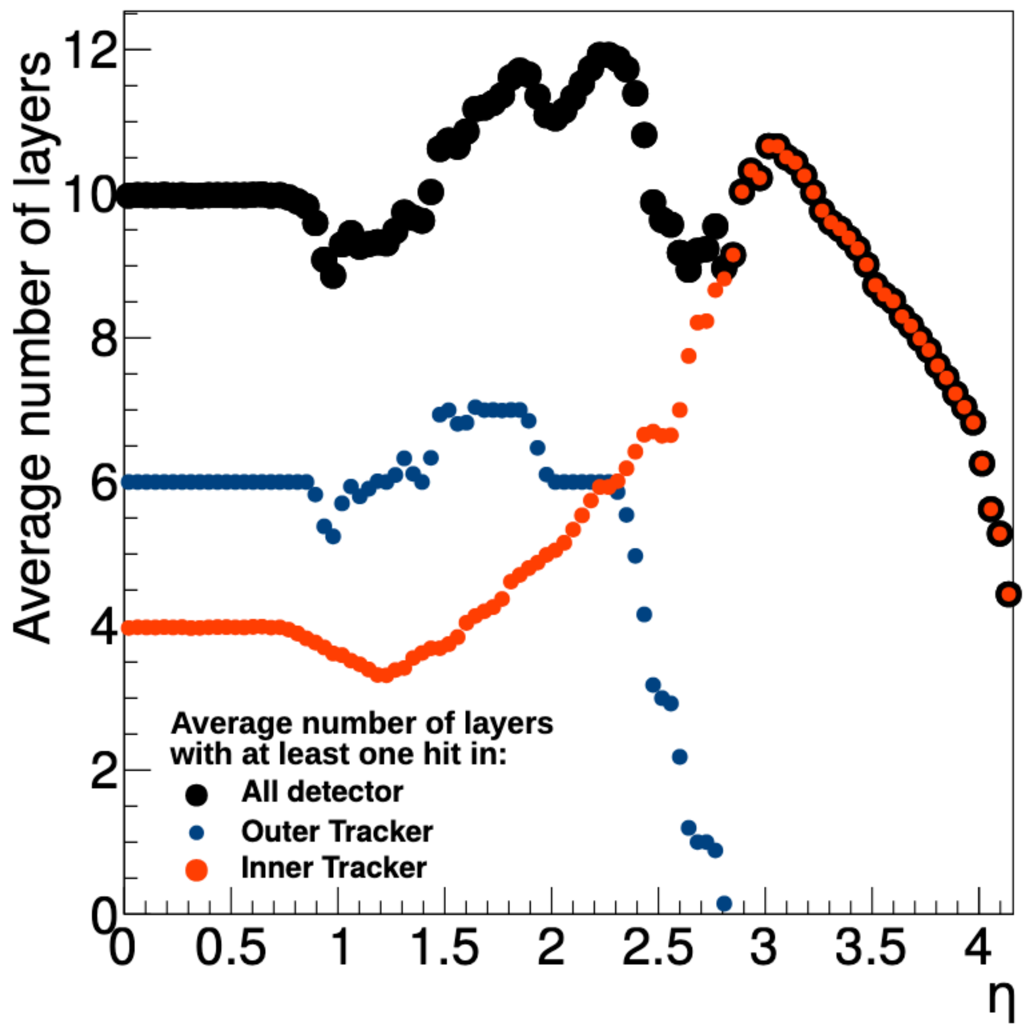
Phase-2 Tracker

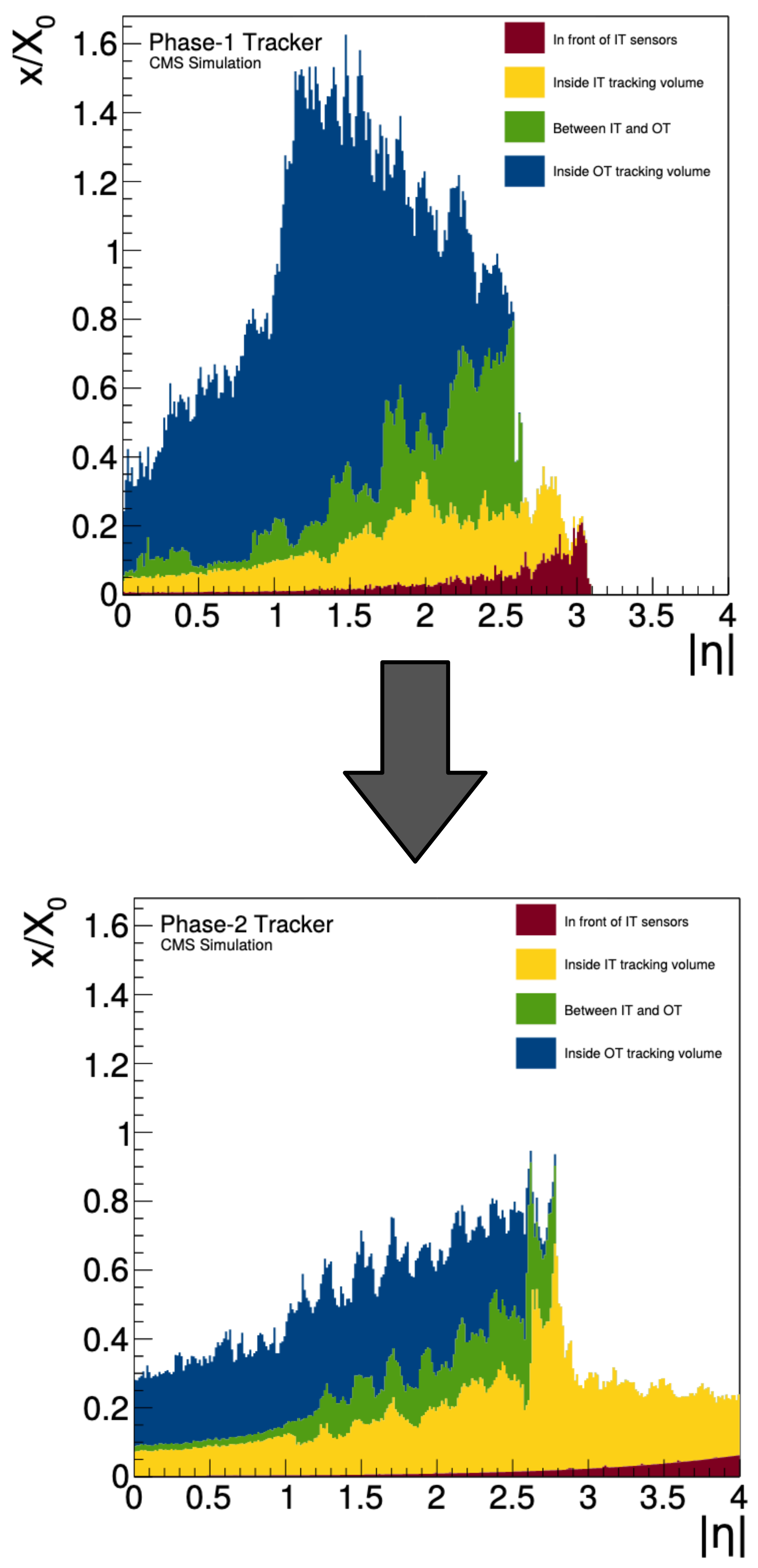
Outer tracker: 6 layers each w/ a pair of sensors

Outer 3 layers: strip-strip (2S) modules, 90 μm x 5cm strips

Inner 3 layers: pixel-strip (PS) modules,
macro-pixel (100 μm x 1.5 mm) + strip (100 μm x 2.5 mm)







Inner tracker: Pixels

4 barrel layers: r ≈ 3, 7, 10, 16 cm

100x150 or 50x50 μm^2 (6x smaller)

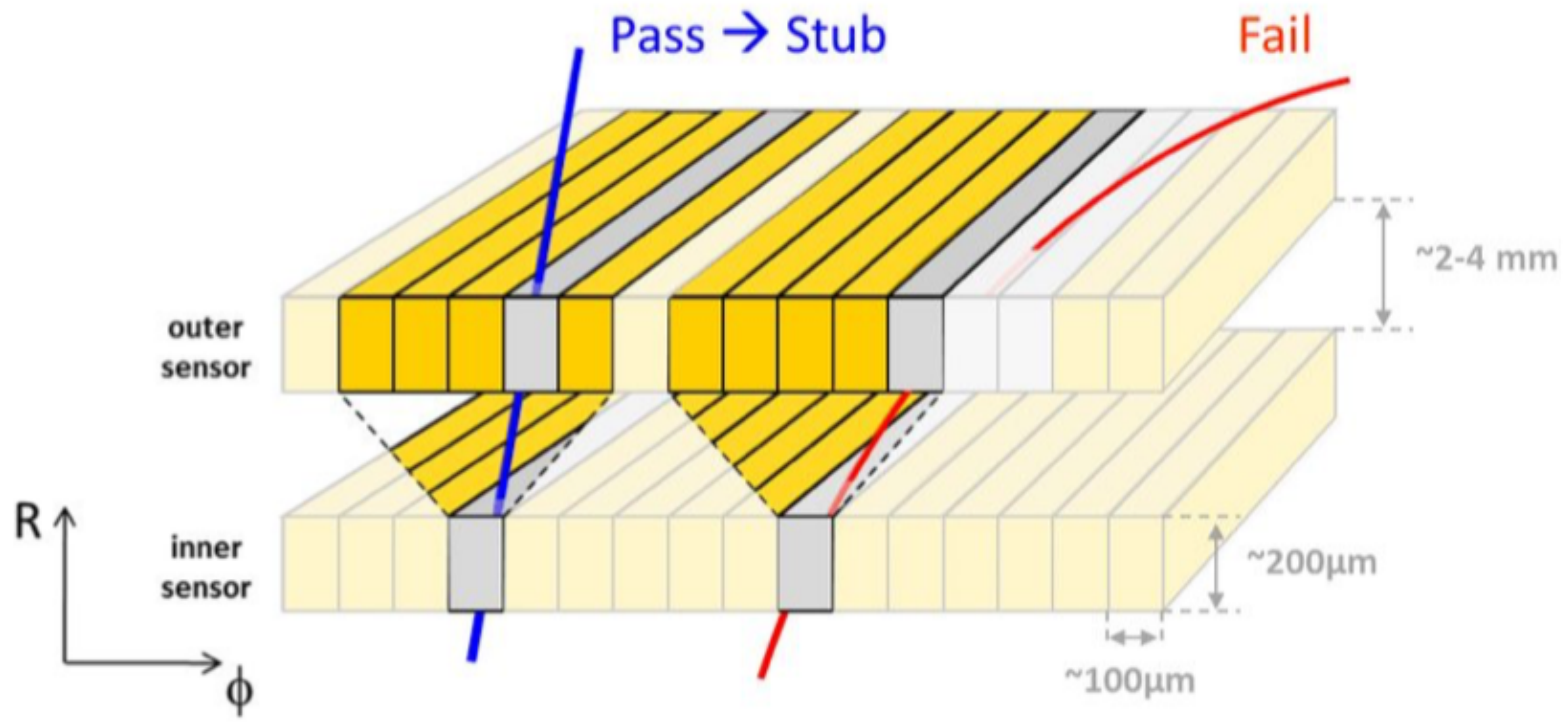
3D sensors in first layer

Addition of forward discs extends η coverage

Reduced material budget

Tracking in the Level-1 trigger

Preserving physics performance at PU = 200 <u>requires</u> tracking at Level-1
Outer tracker is designed specially for this

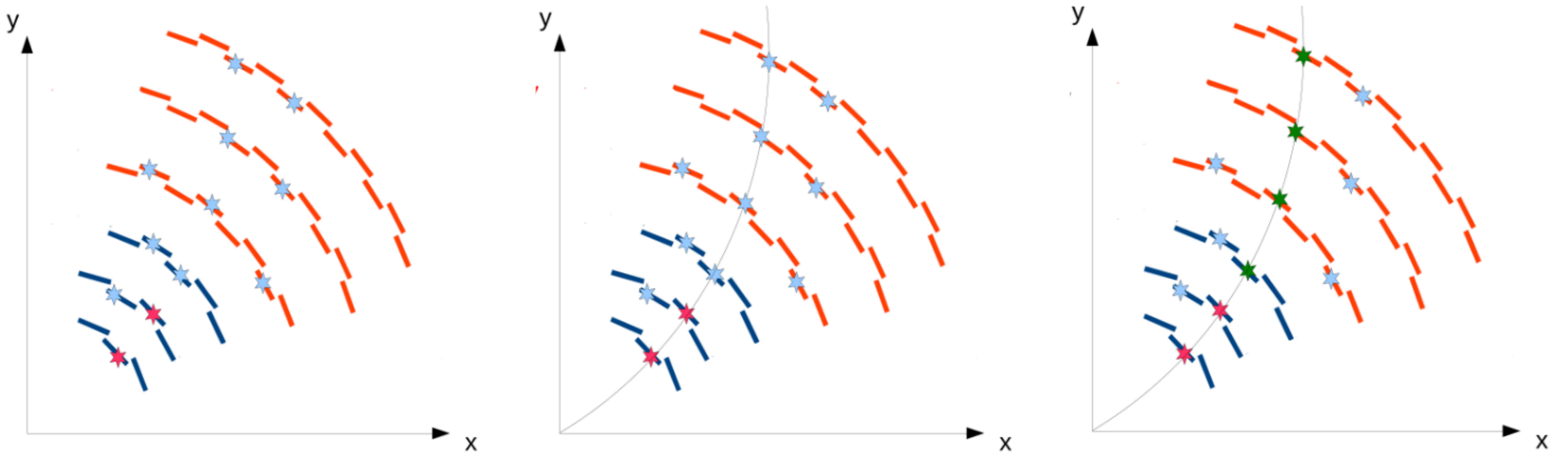


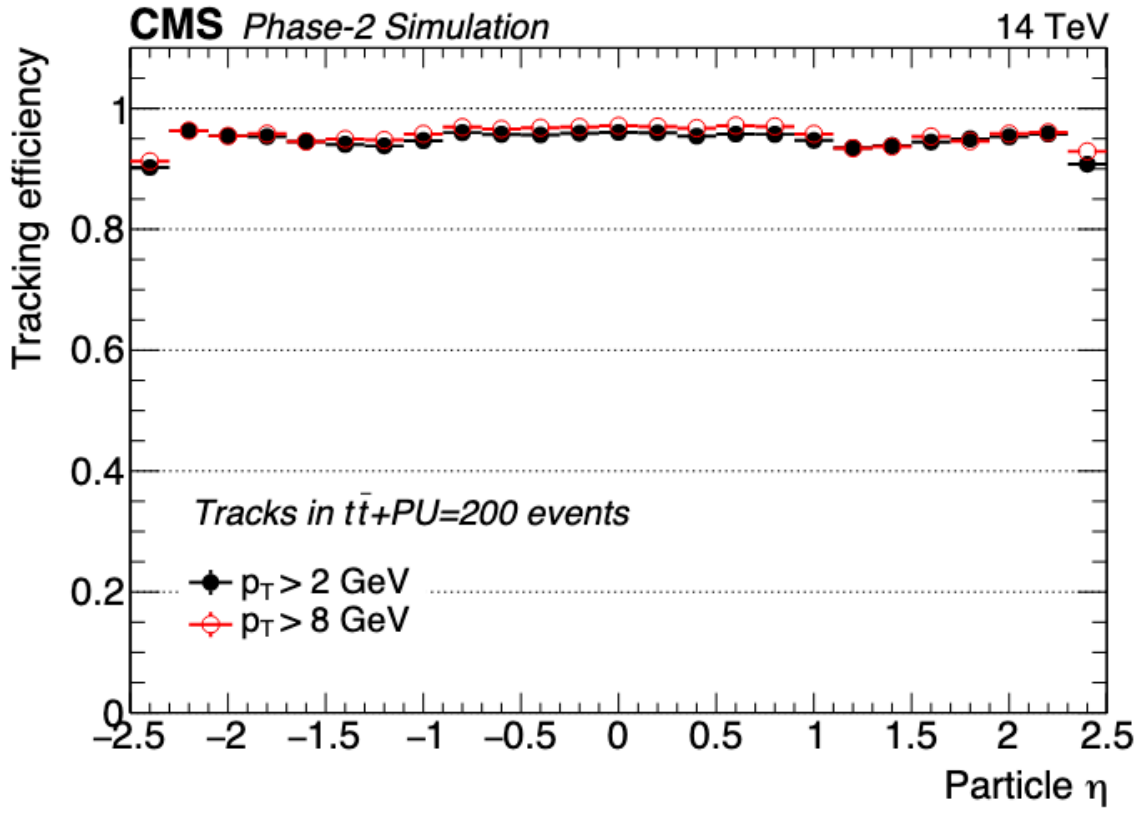
- Each layer consists of a pair of sensors: "p_T modules"
- Read out with single ASIC
- Filter on "stubs", pairs of hits from track of $p_T > 2$ GeV

→ 97% data reduction

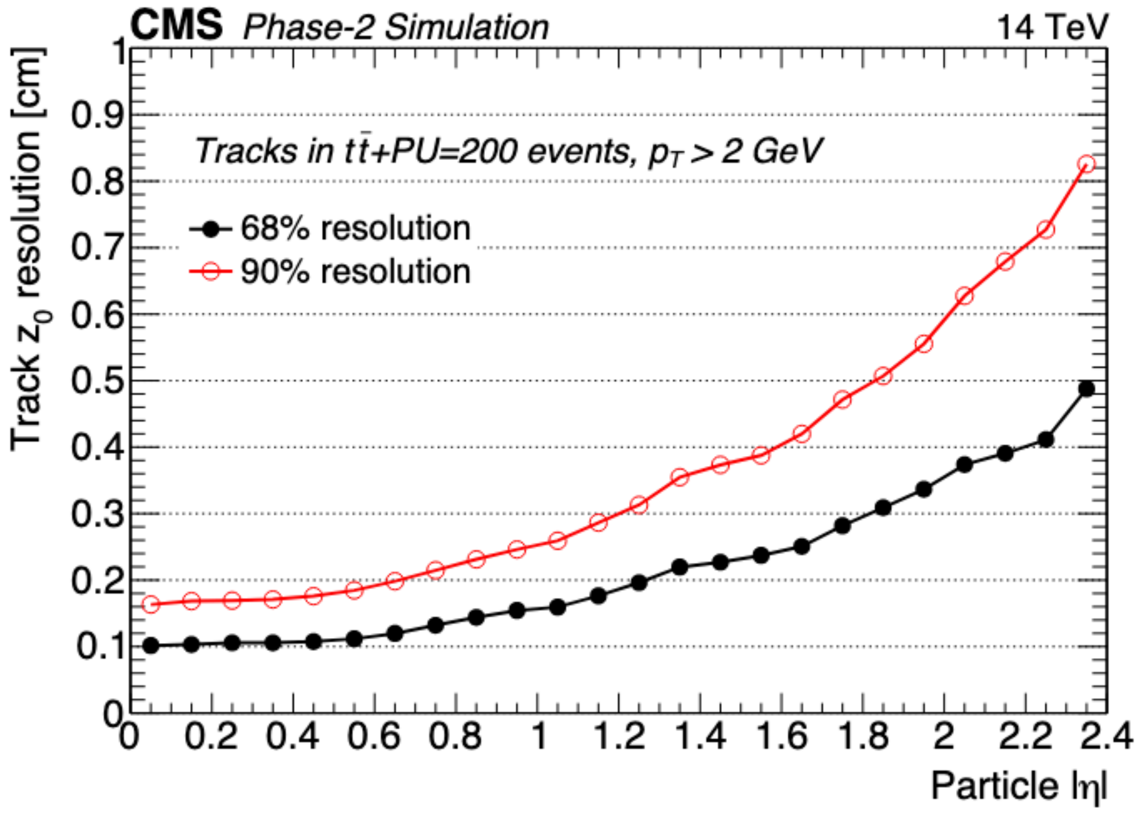
Trajectories reconstructed on dedicated FPGAs:

- Seeds formed from stubs on adjacent layers ("tracklets")
- Tracklets projected into other layers & matched to compatible stubs
- Trajectory is estimated via a Kalman filter





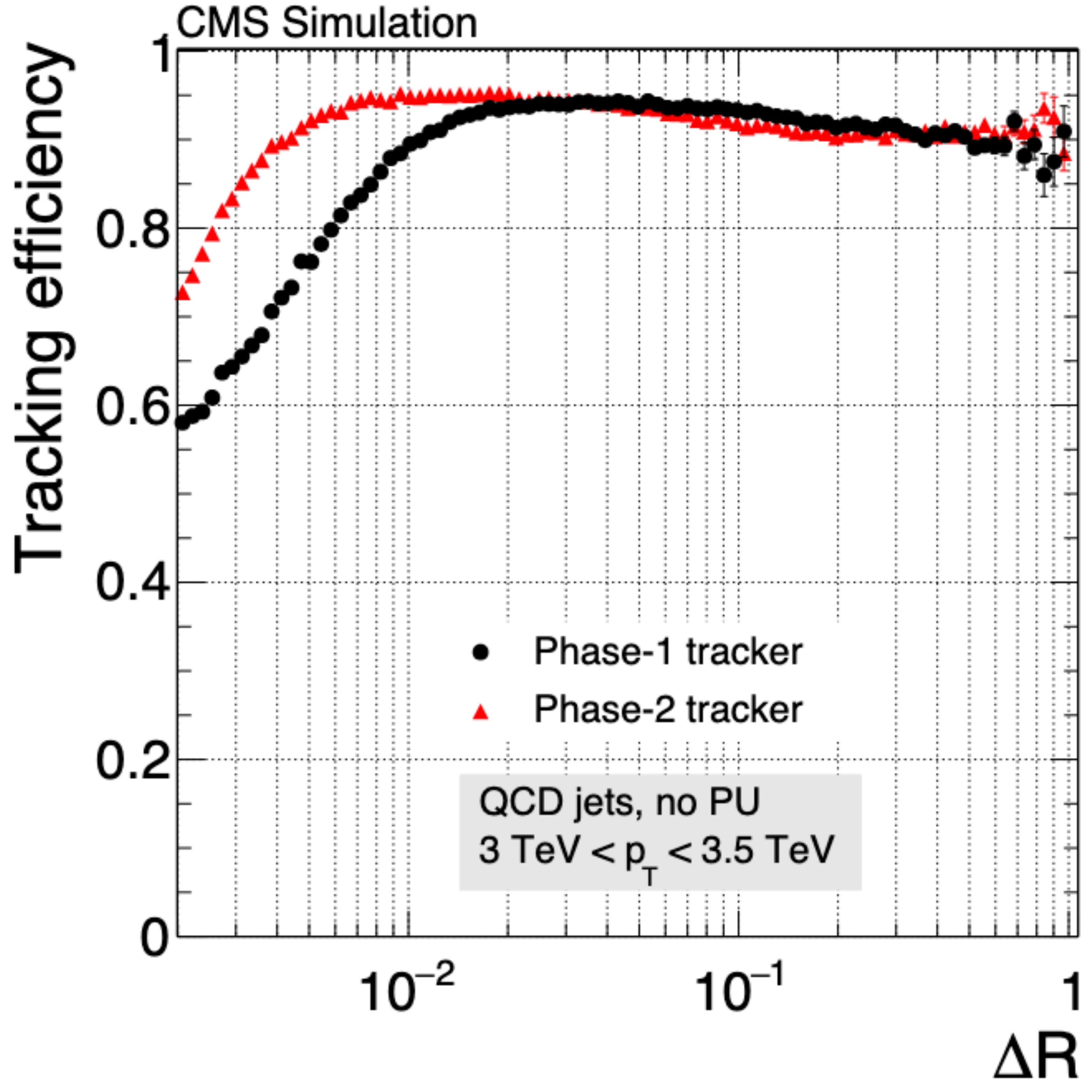
>=6 layers for all η
→95% tracking efficiency

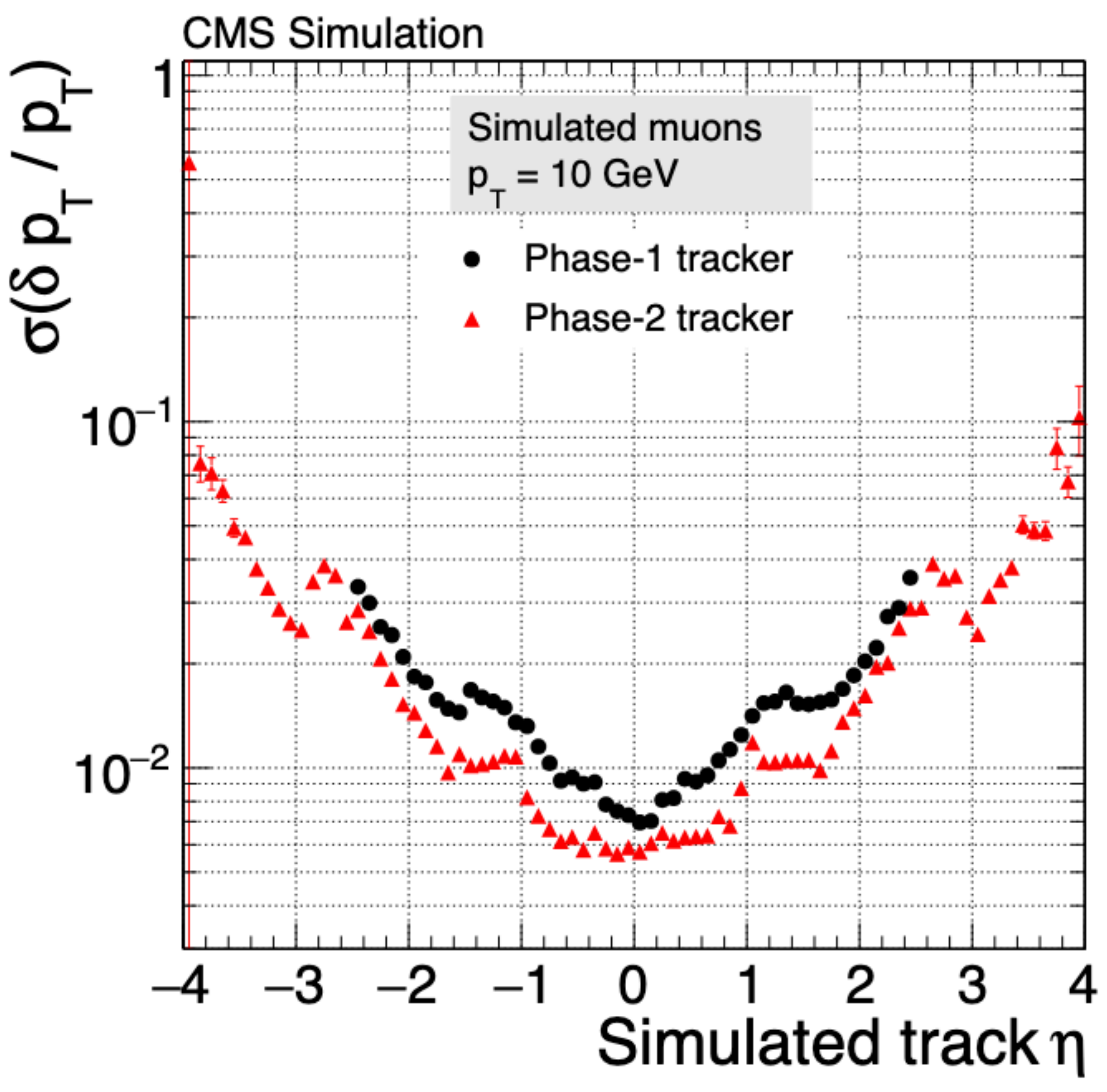


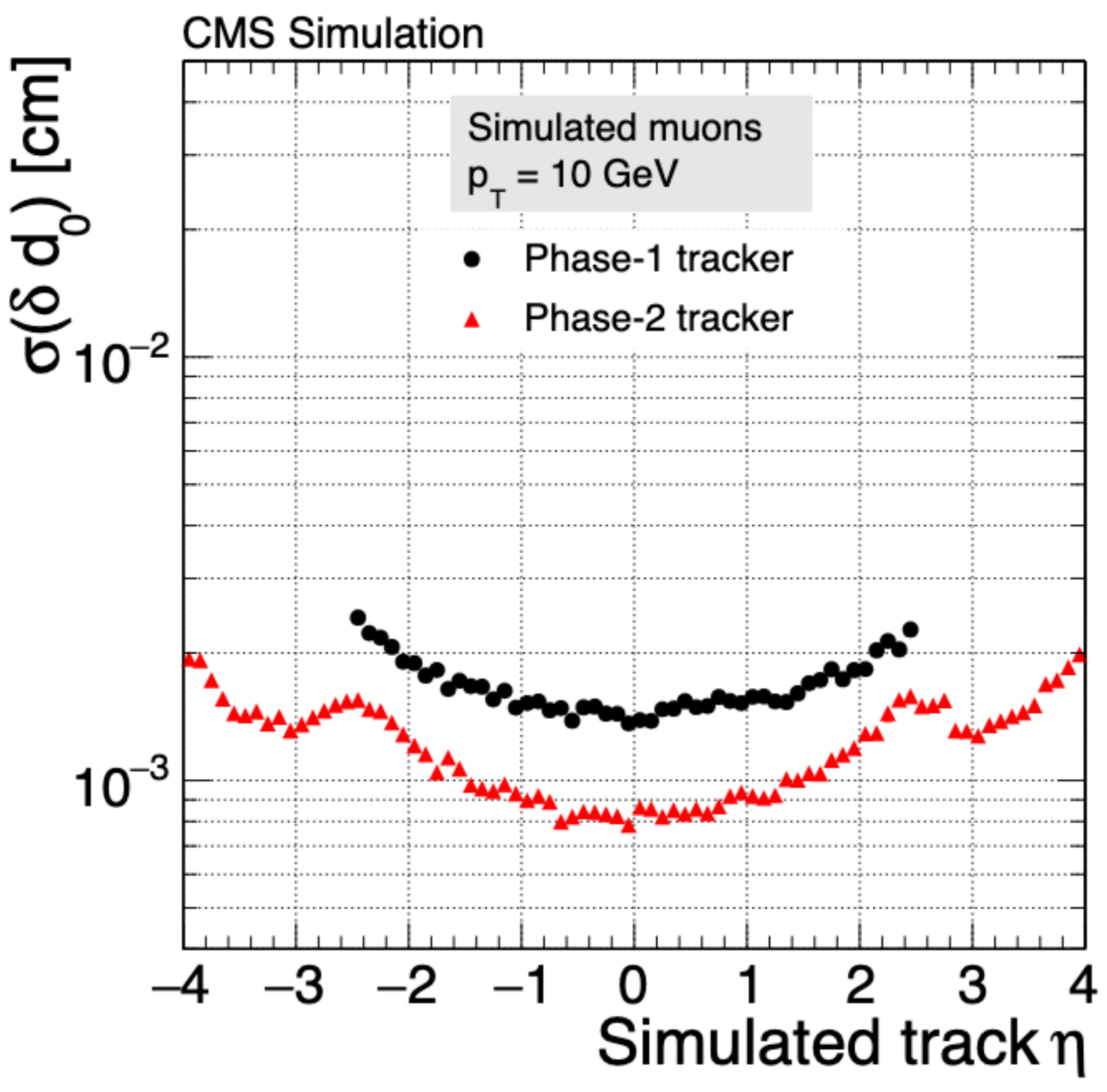
< 1 cm resolution in z
thanks to macro-pixels

Offline tracking performance

Improved momentum & impact parameter resolution

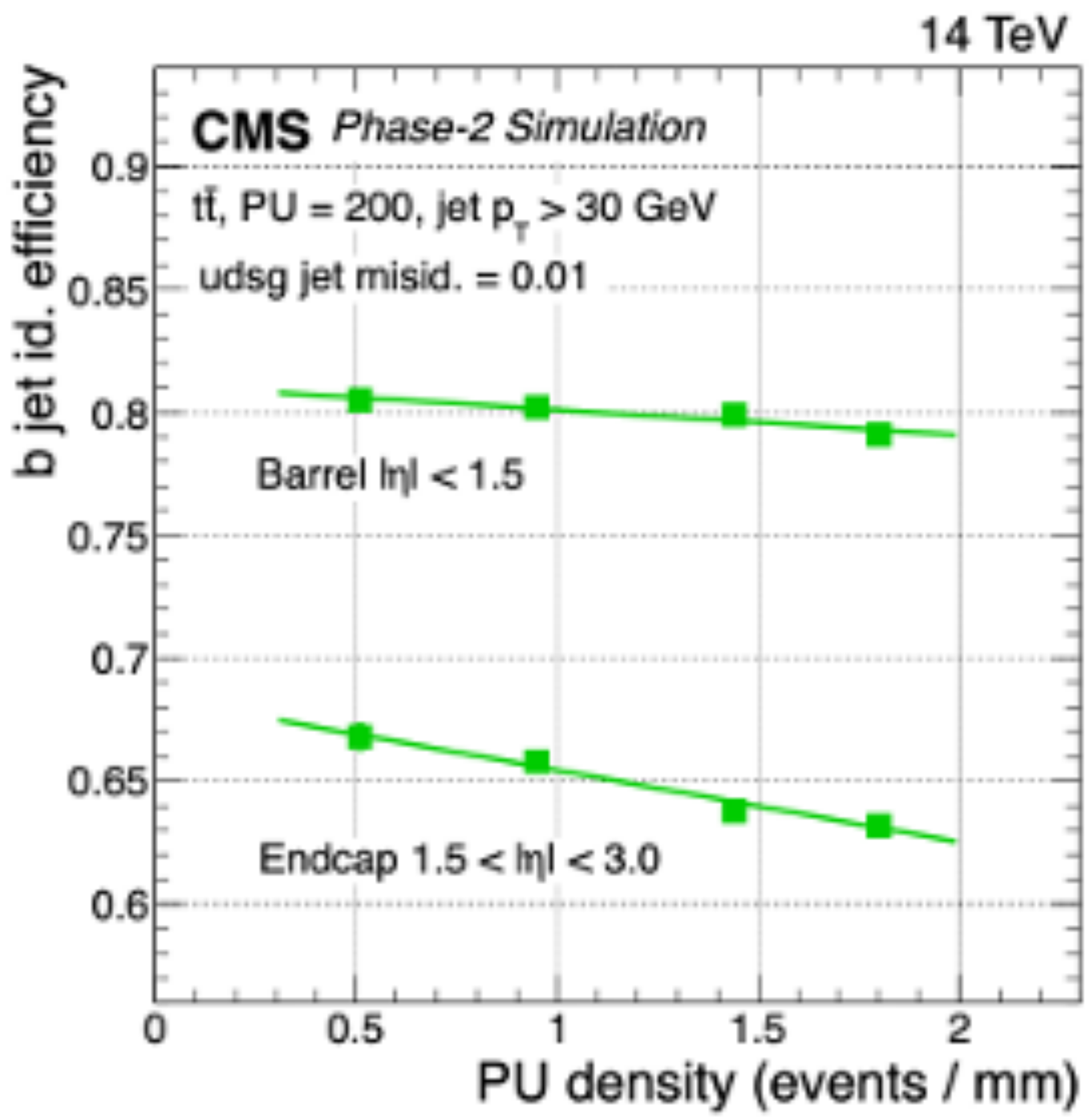


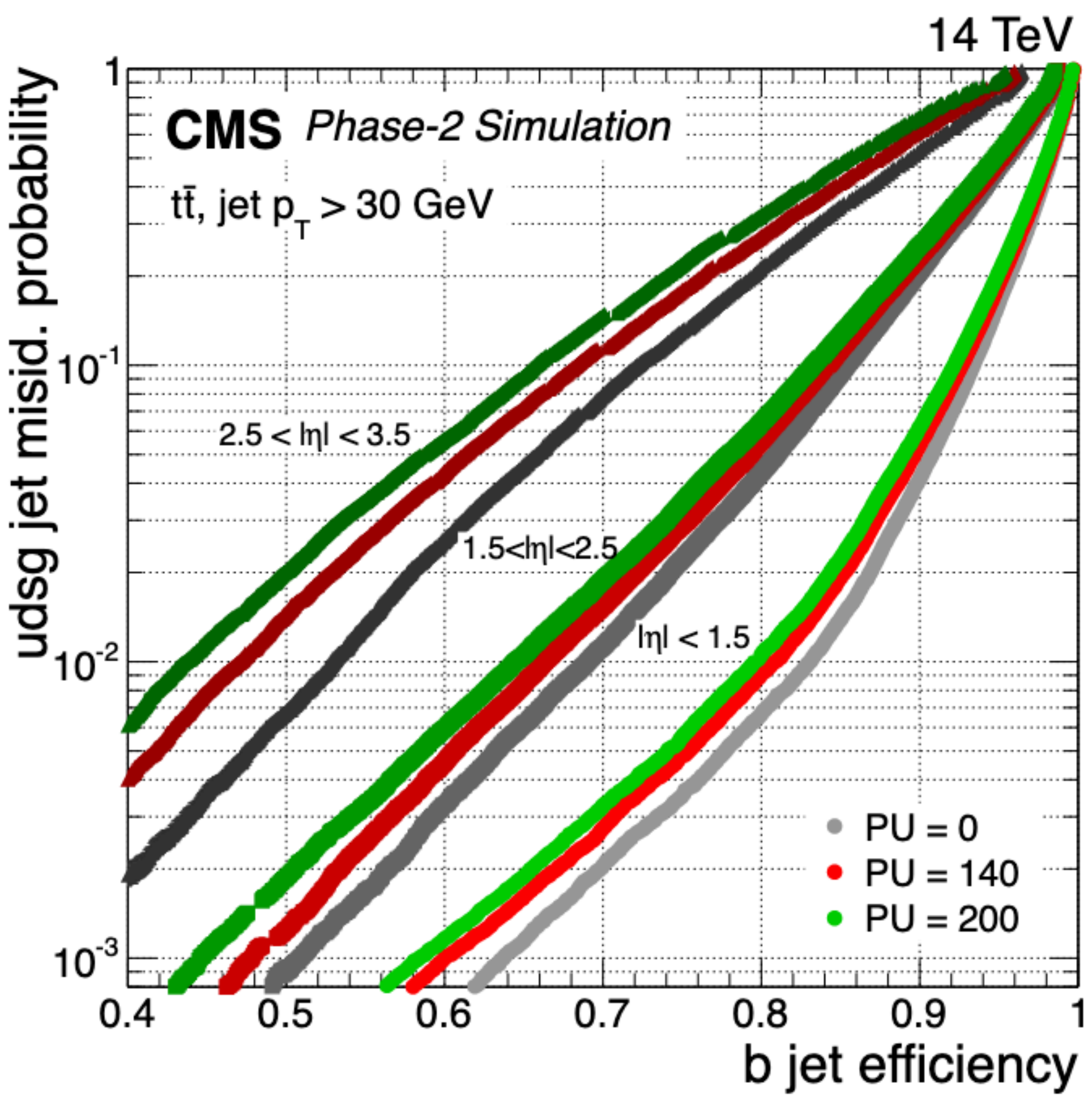




Improved efficiency in the core of TeV jets

Modest dependence of b-tagging on local pile-up density

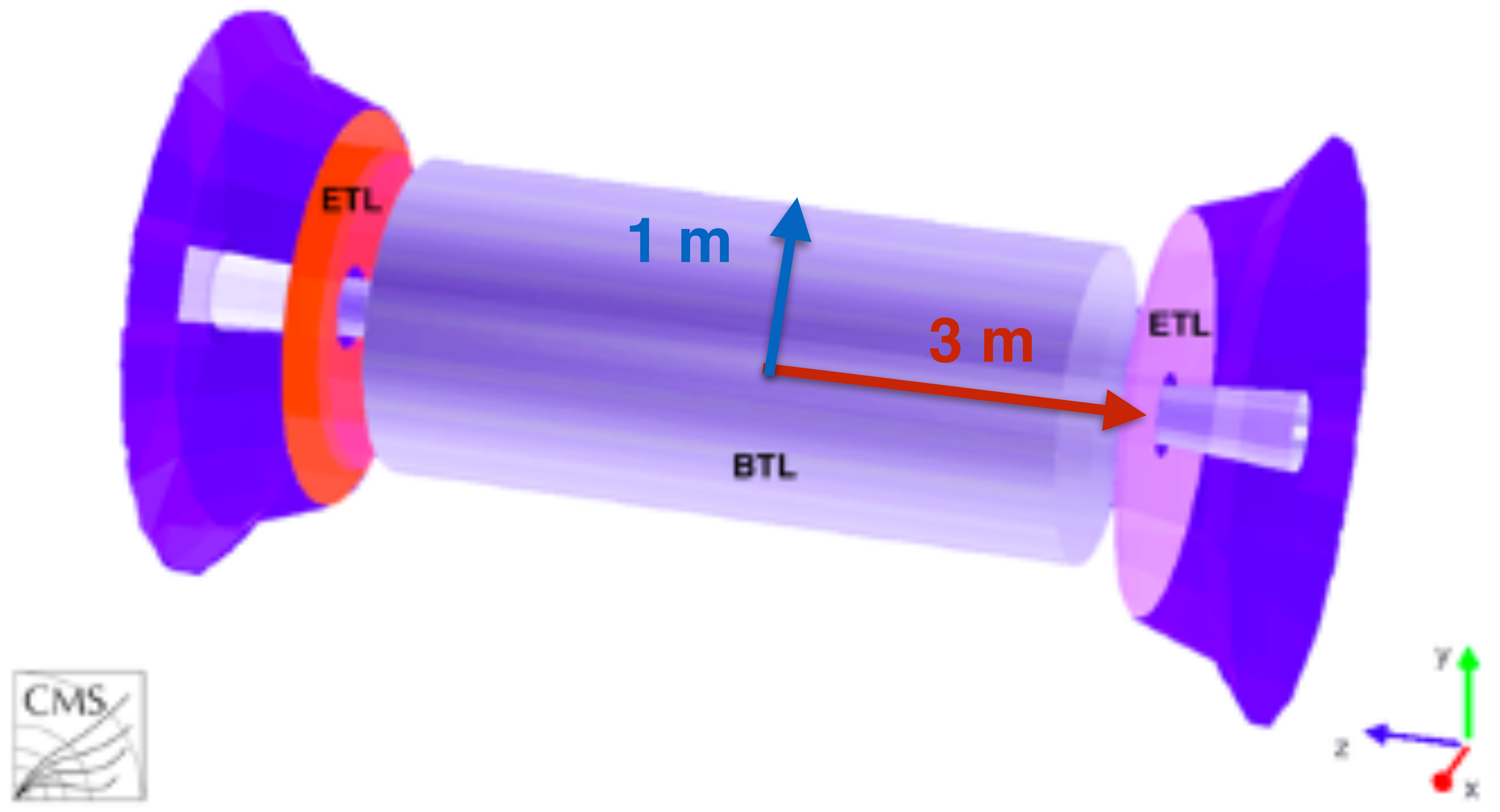


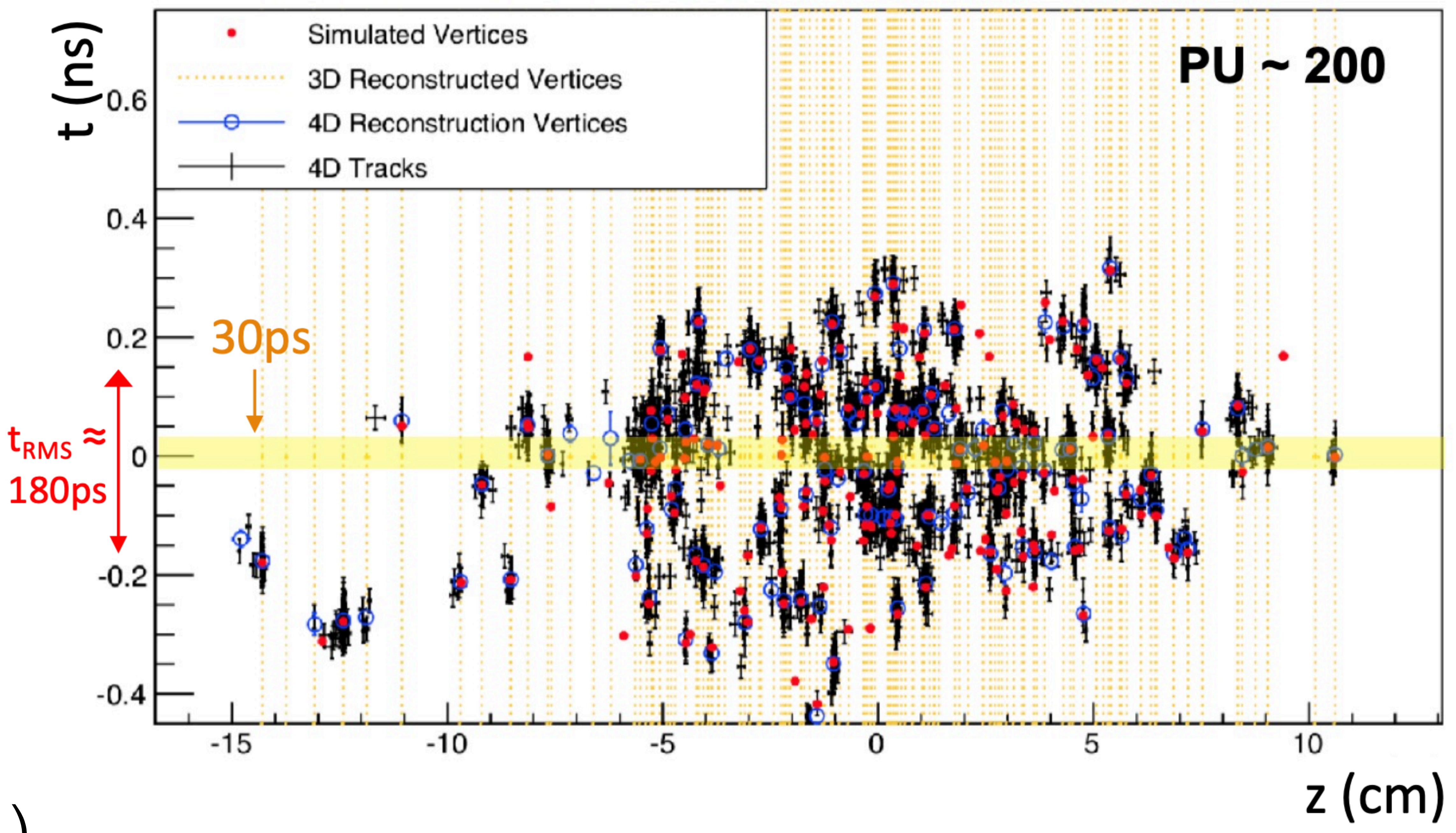


Flavor tagging at very forward η for the first time

MIP timing detector (MTD)

Two thin timing layers between tracker & calorimeter systems





Barrel Timing Layer (BTL)

Technology: LYSO + SiPM
Coverage: $|\eta| < 1.5$, $p_T > 0.7$ GeV
Time resolution: 30 ps
Tolerance: $1.9 \times 10^{14}\ n_{eq}/cm^2$

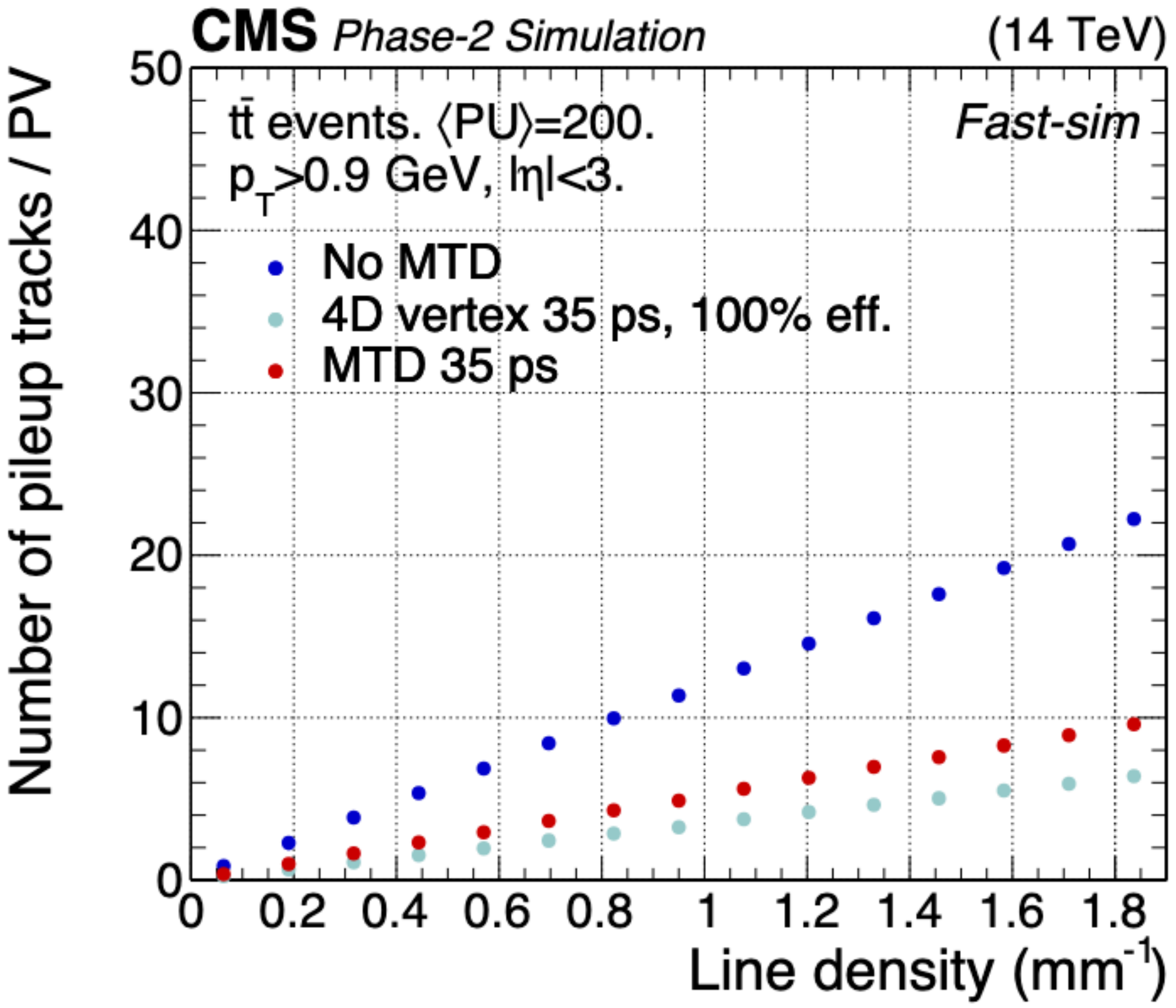
Endcap Timing Layer (ETL)

Technology: LGAD
Coverage: $1.6 < |\eta| < 3$
Time resolution: 30-40 ps
Tolerance: up to $1.6 \times 10^{15}\ n_{eq}/cm^2$

@ PU = 200 15% of vertices are merged in without timing
Vertices are spread across bunch with an RMS of 180 ps
With 30 ps time resolution only 1% of vertices are merged

Pile-up mitigation with the MTD

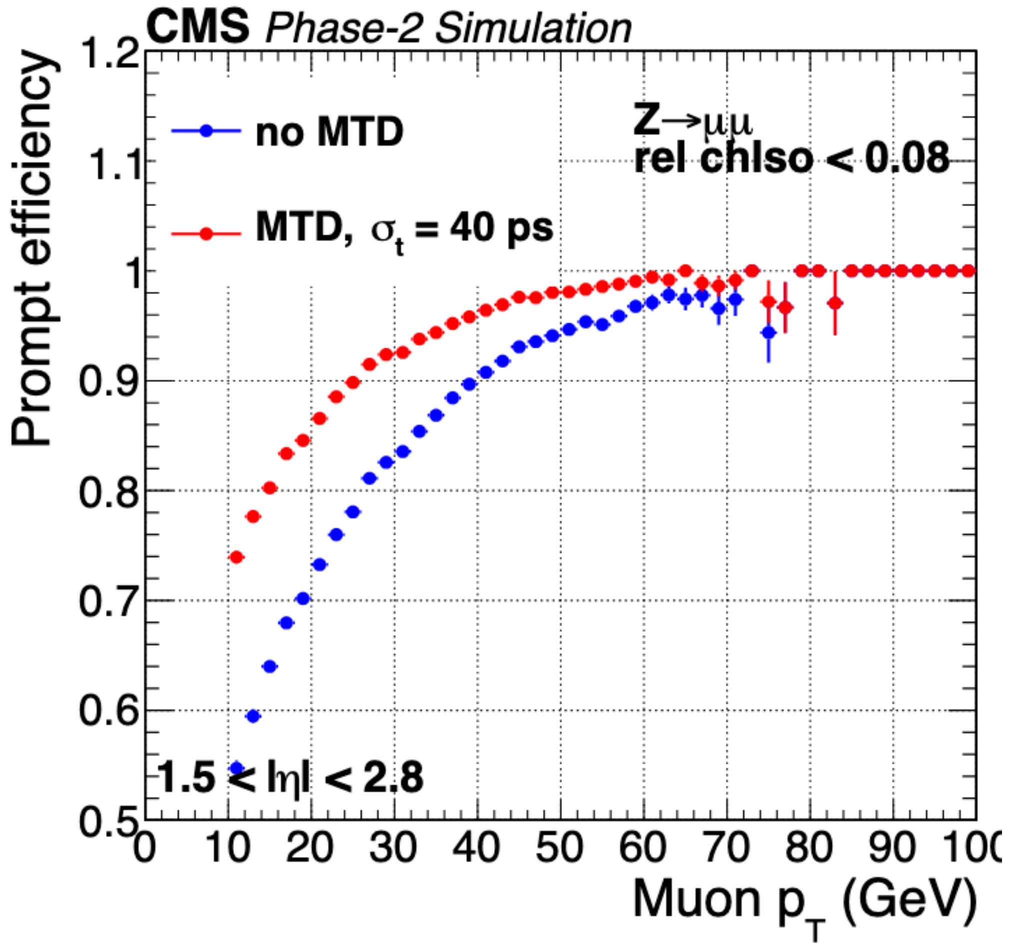
4D reconstruction of primary vertices



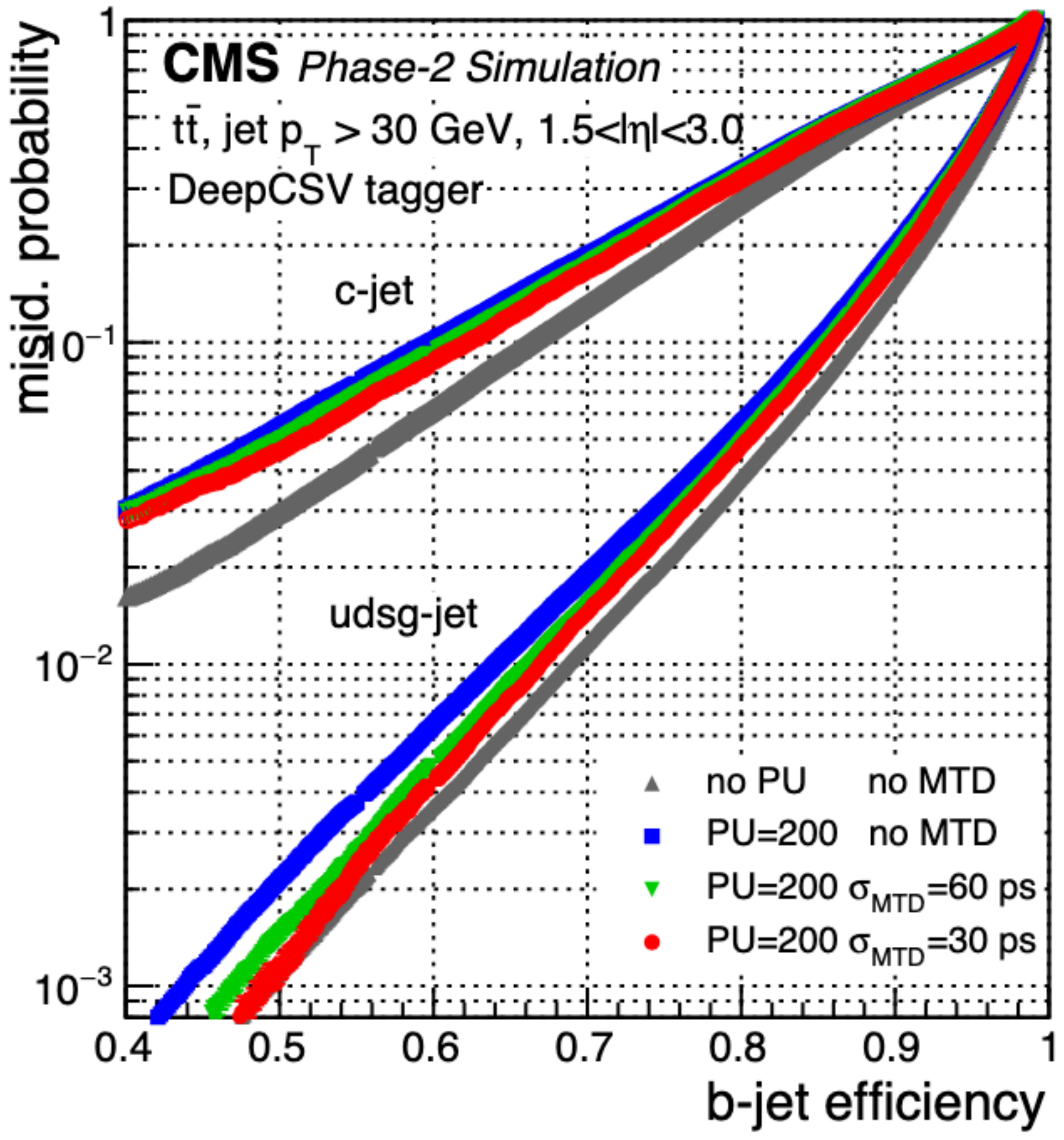
Reduced the number of pileup tracks that are incorrectly associated to primary vertex

reduces impact of PU on high-level objets, e.g.,

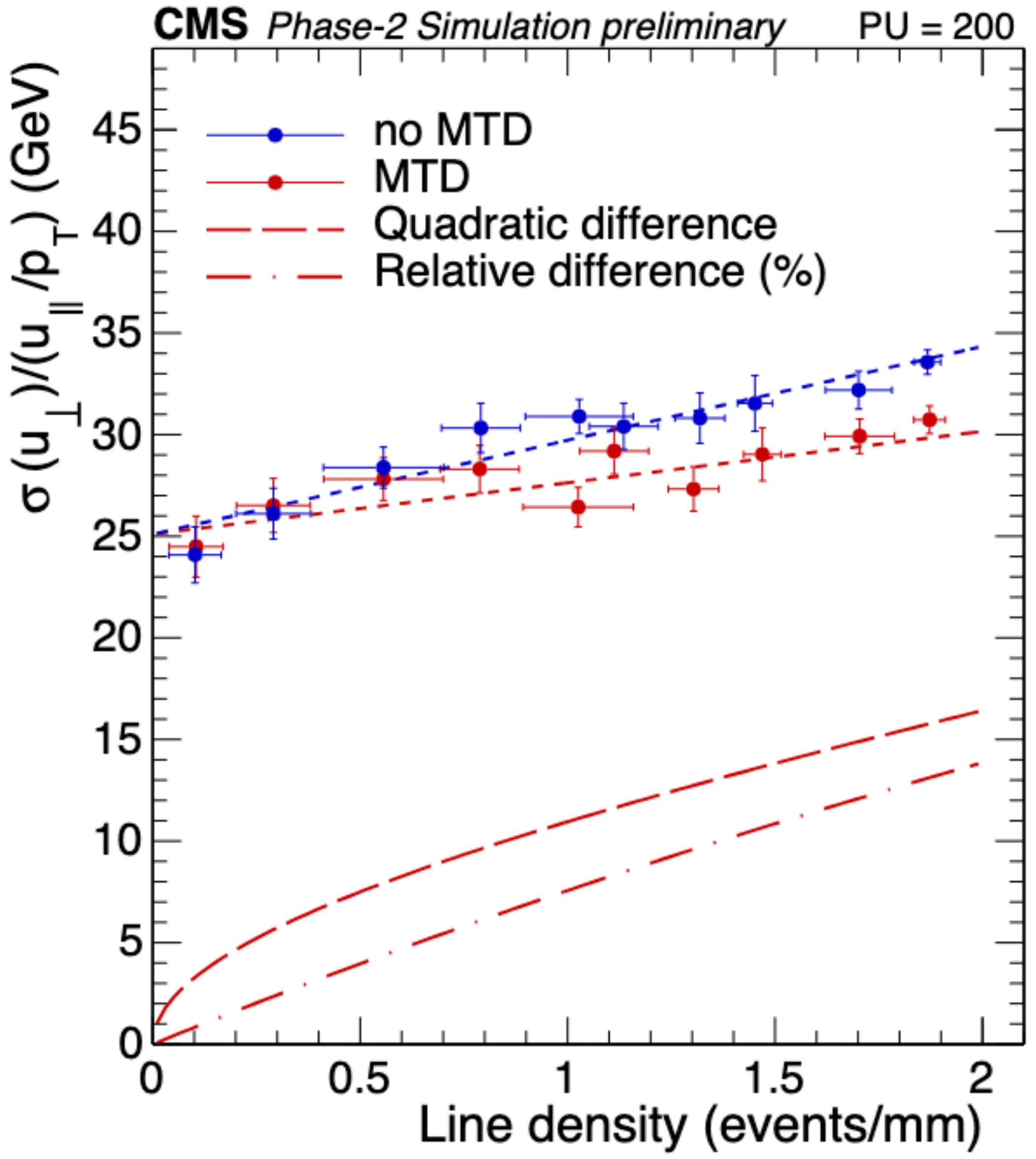
isolation



flavor tagging



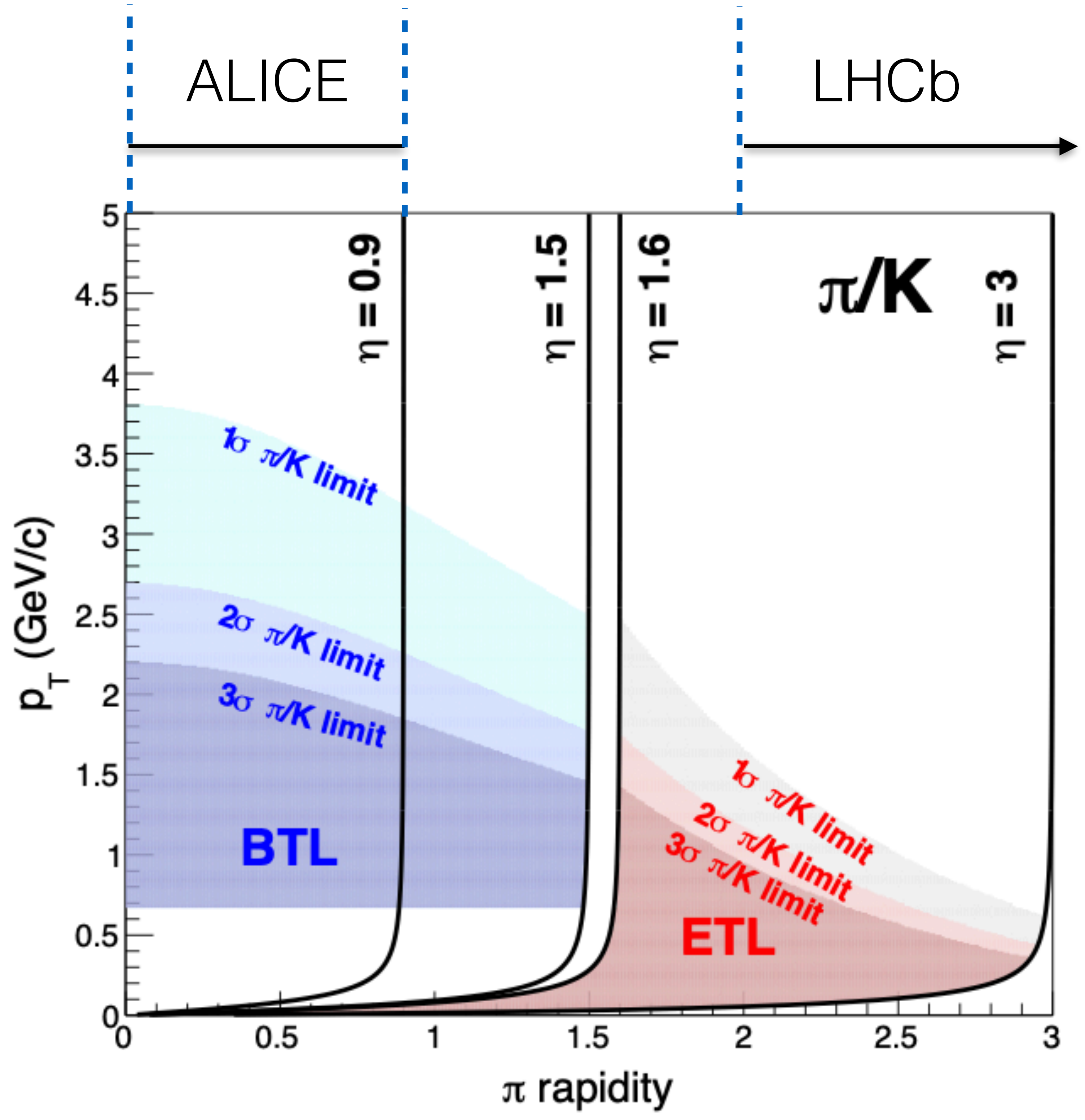
missing E_T



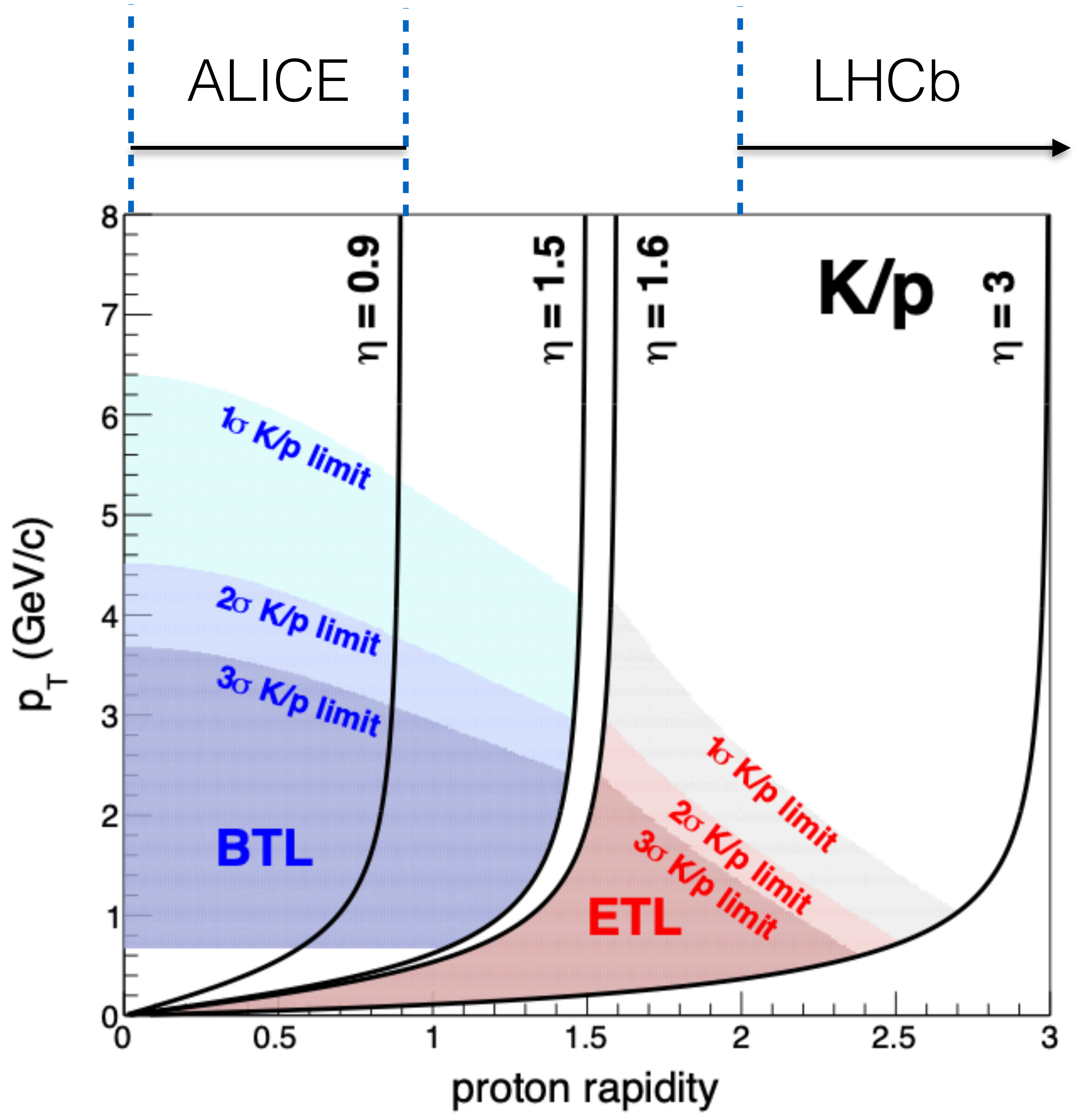
Particle identification w/ MTD

MTD provides PID over large acceptance
Complementary w/ ALICE & LHCb

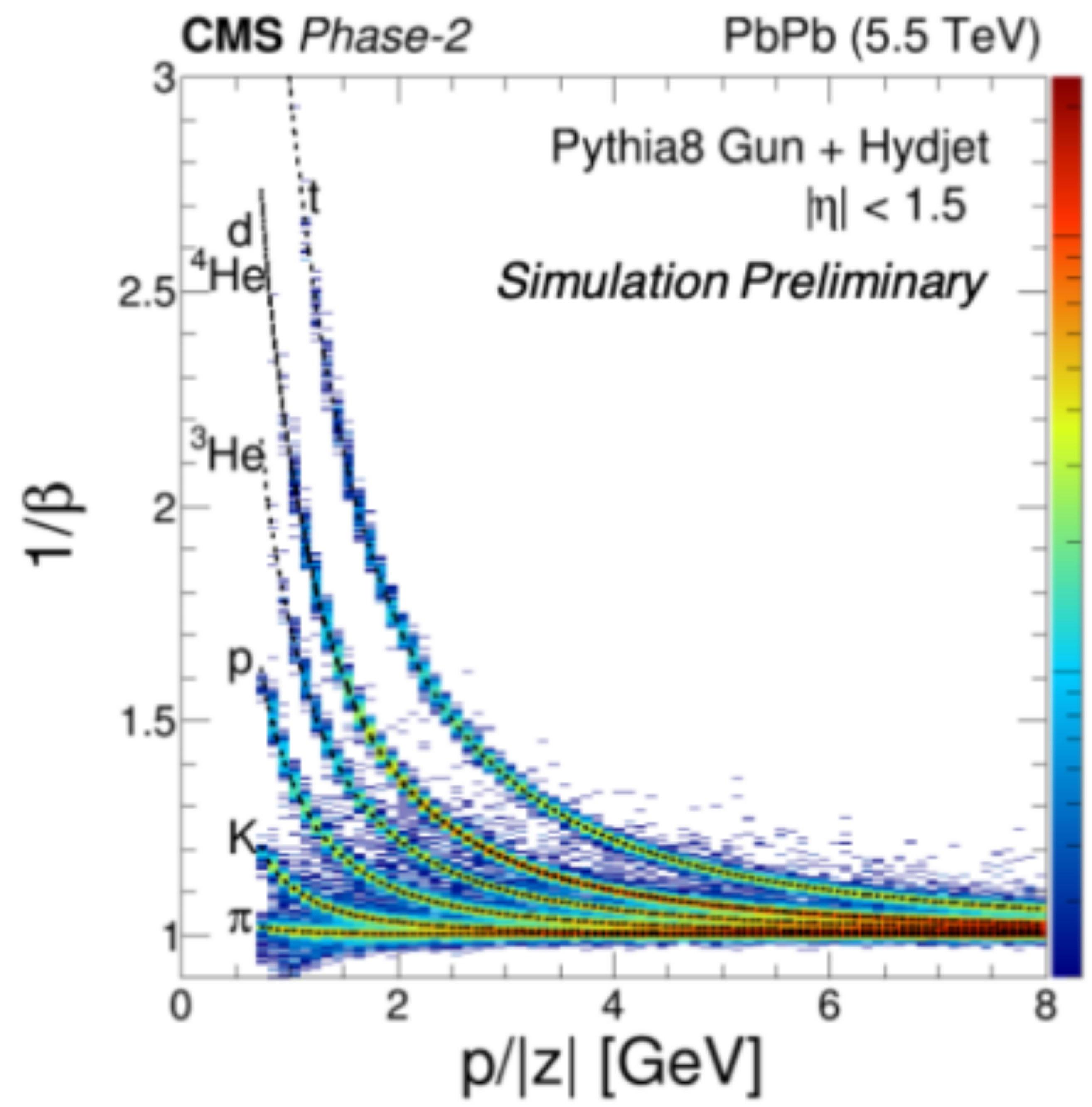
Experiment	η coverage	r (m)	σ_T (ps)	r/σ_T (x100)
CMS-MTD	|η| < 3.0	1.16	30	3.87
ALICE-TOF	|η| < 0.9	3.7	56	6.6
STAR-TOF	|η| < 0.9	2.2	80	2.75



π/K separation up to p ≈ 2.5 GeV



K/p separation up to p ≈ 5 GeV



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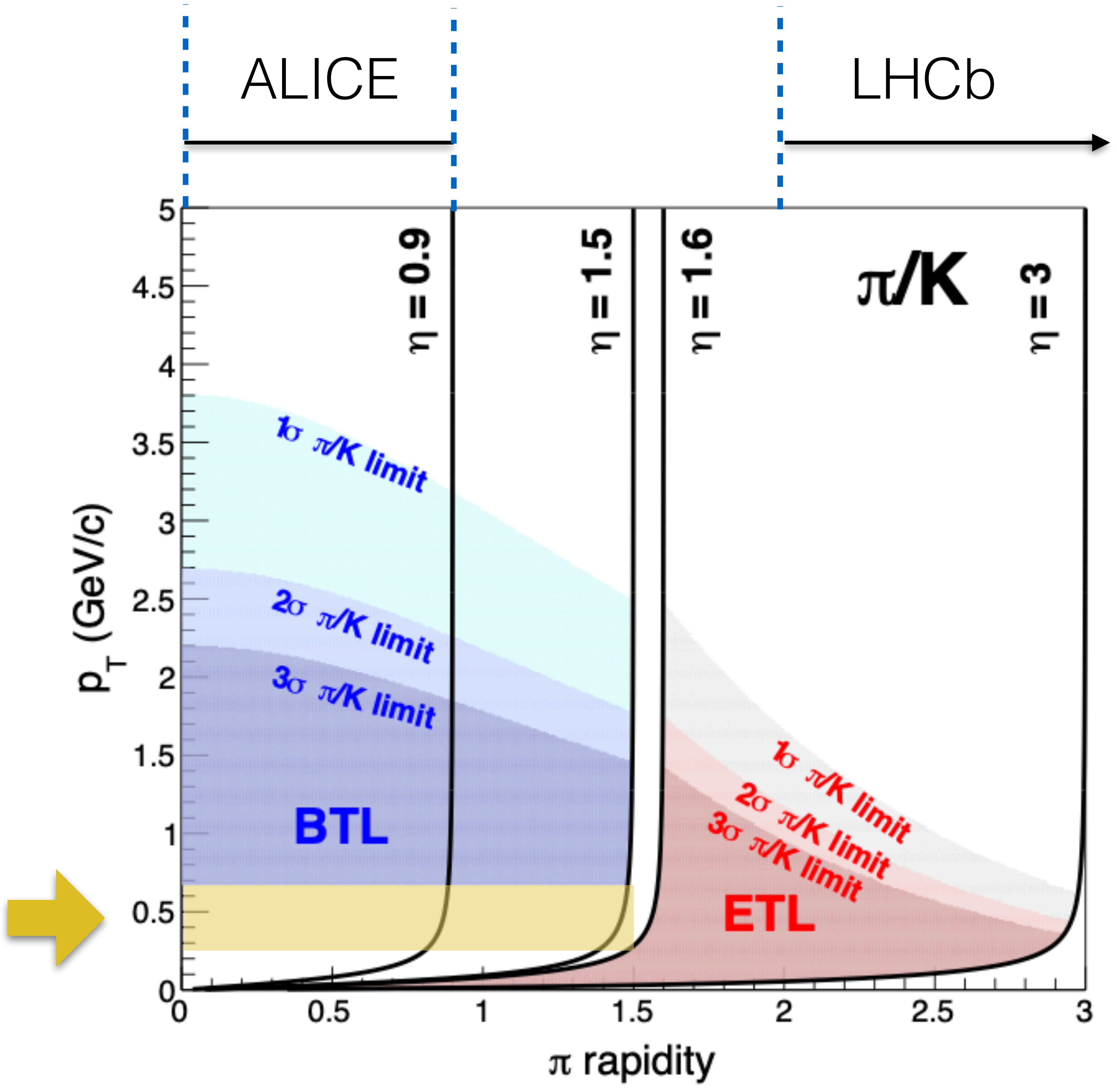

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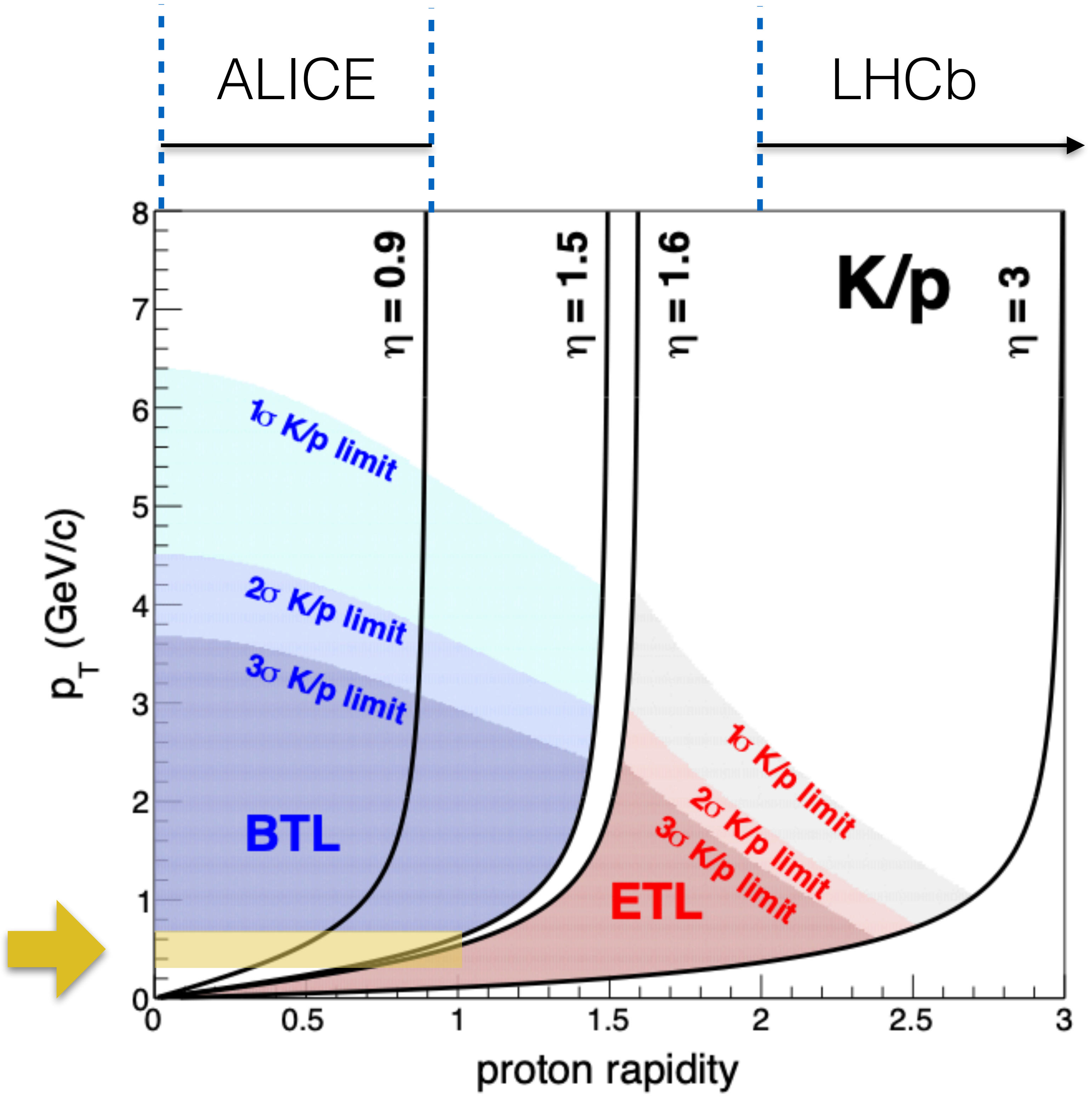
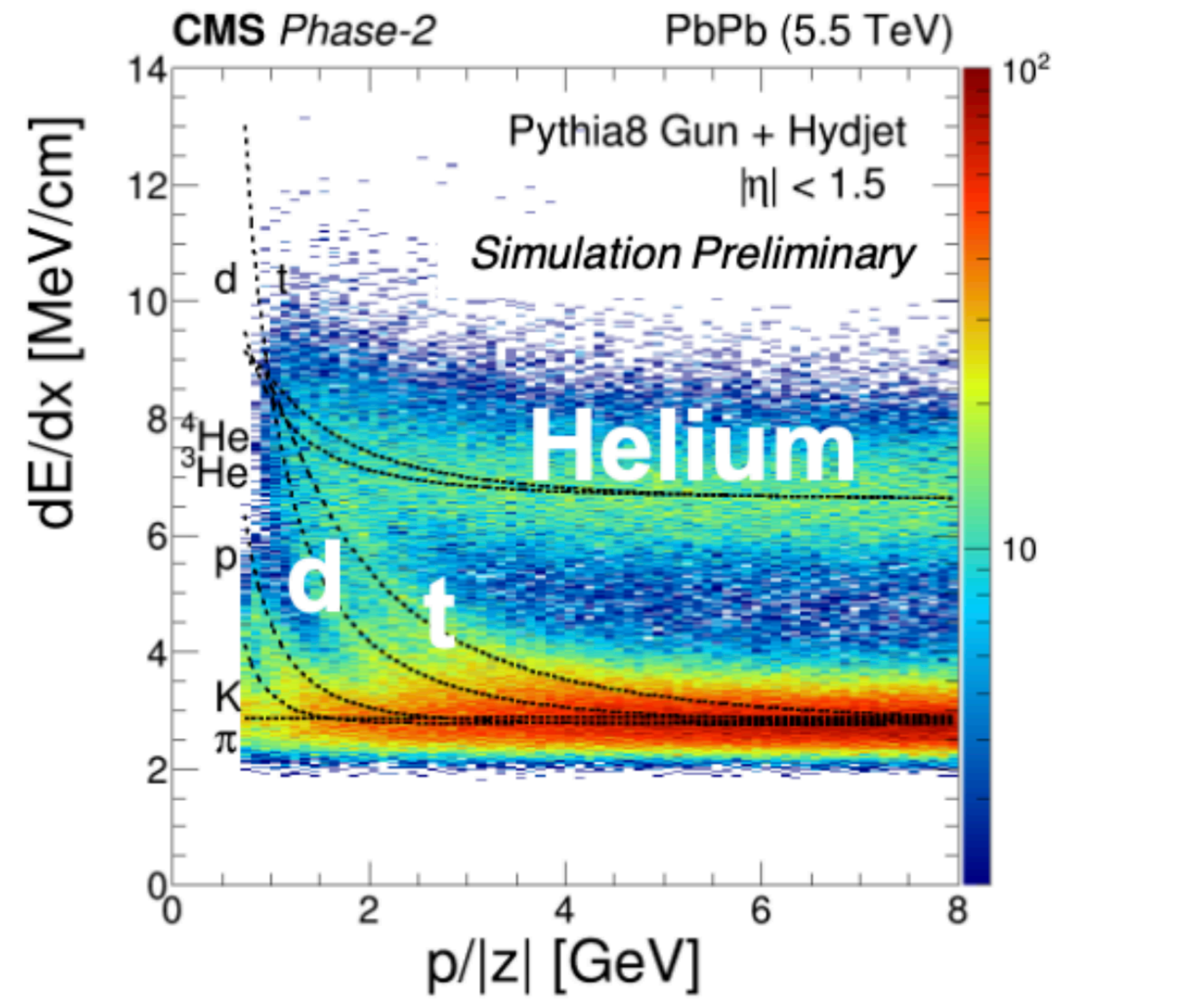


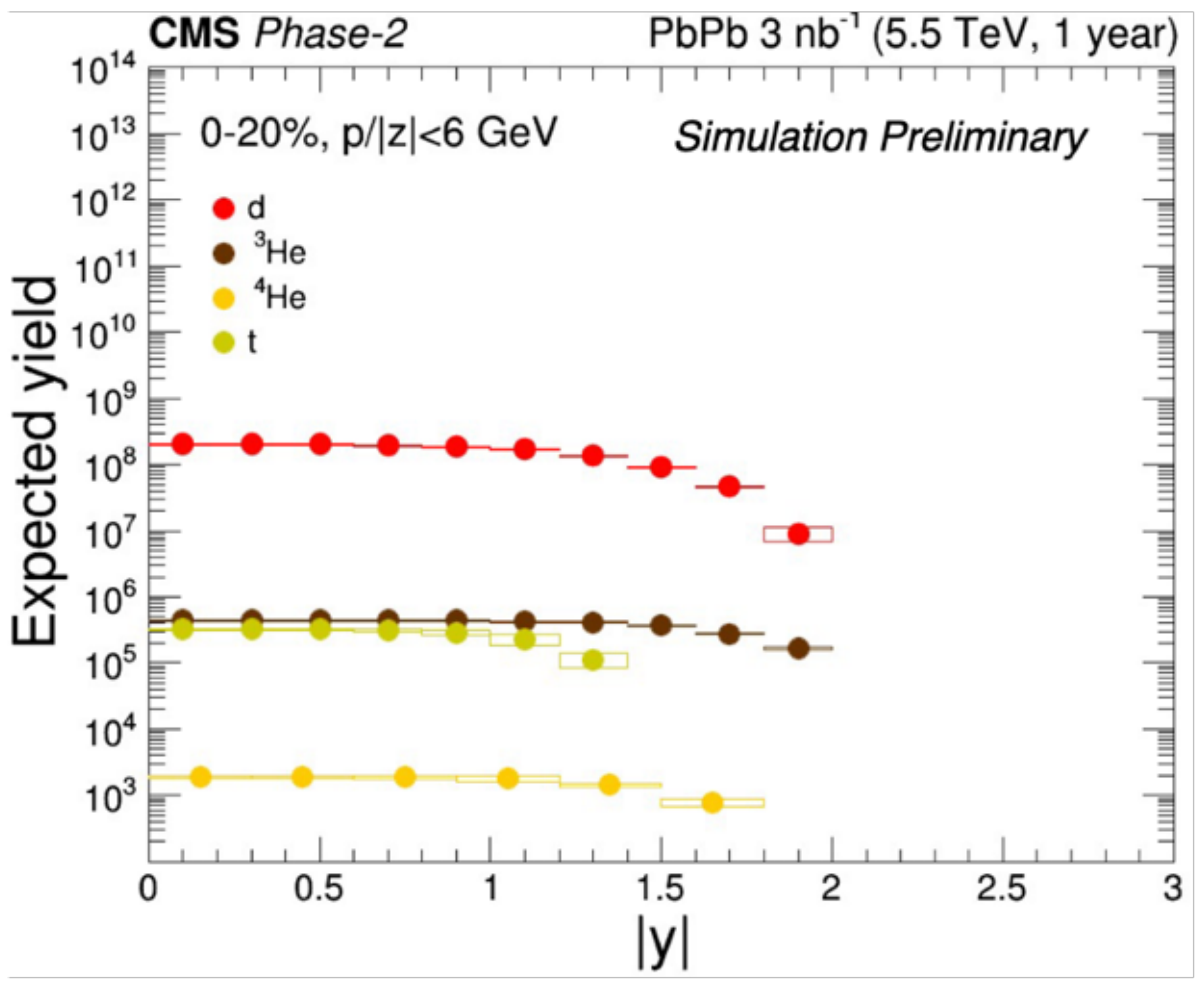
K/p separation up to p ≈ 5 GeV

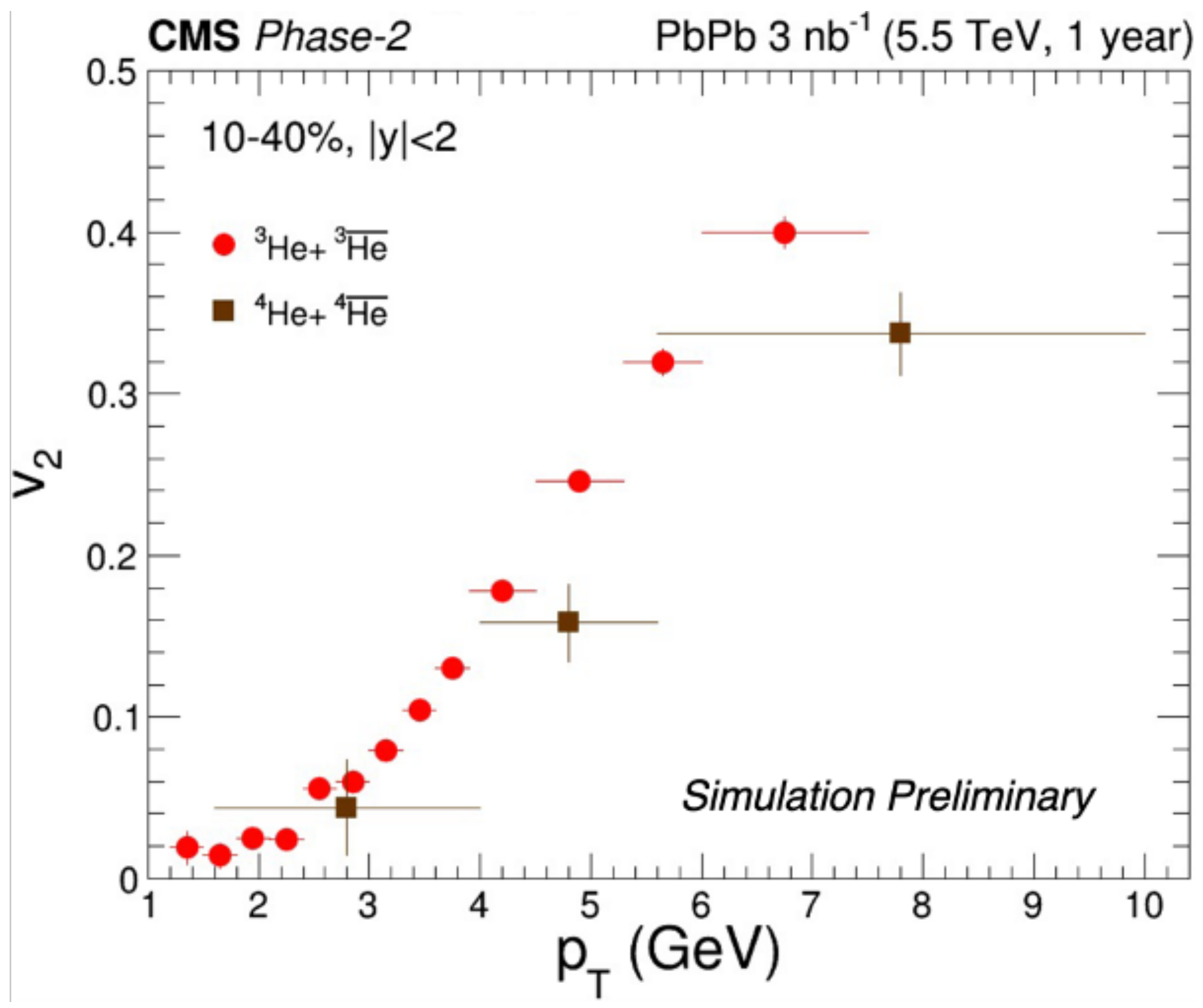


MTD + pixel dE/dx can identify d, t, ^{3}He & ^{4}He
dE/dx used to separate d from ^{4}He by charge

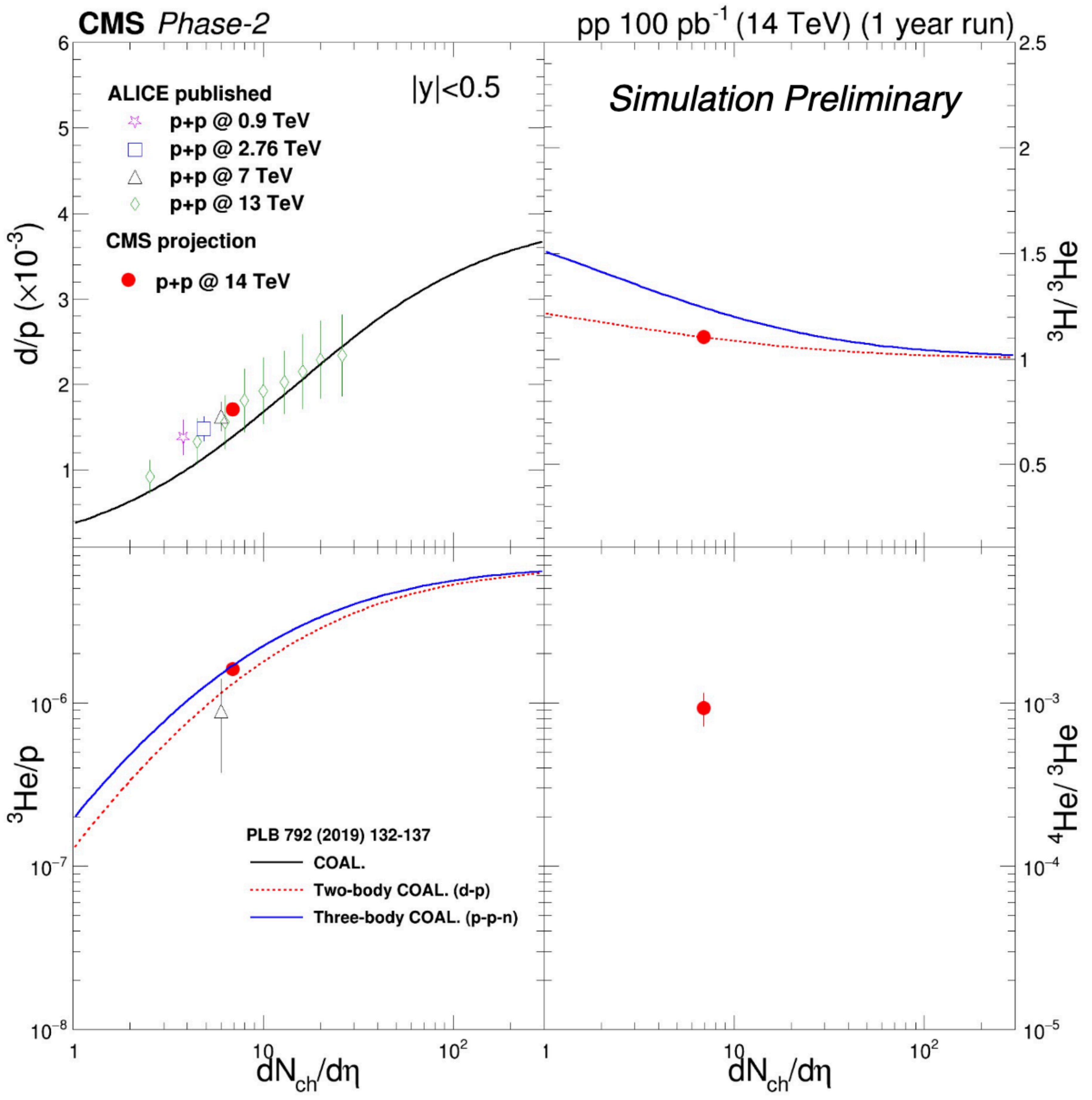
Light nuclei

Heavy ions: Light nuclei are sensitive probes of statistical hadronization and collective flow

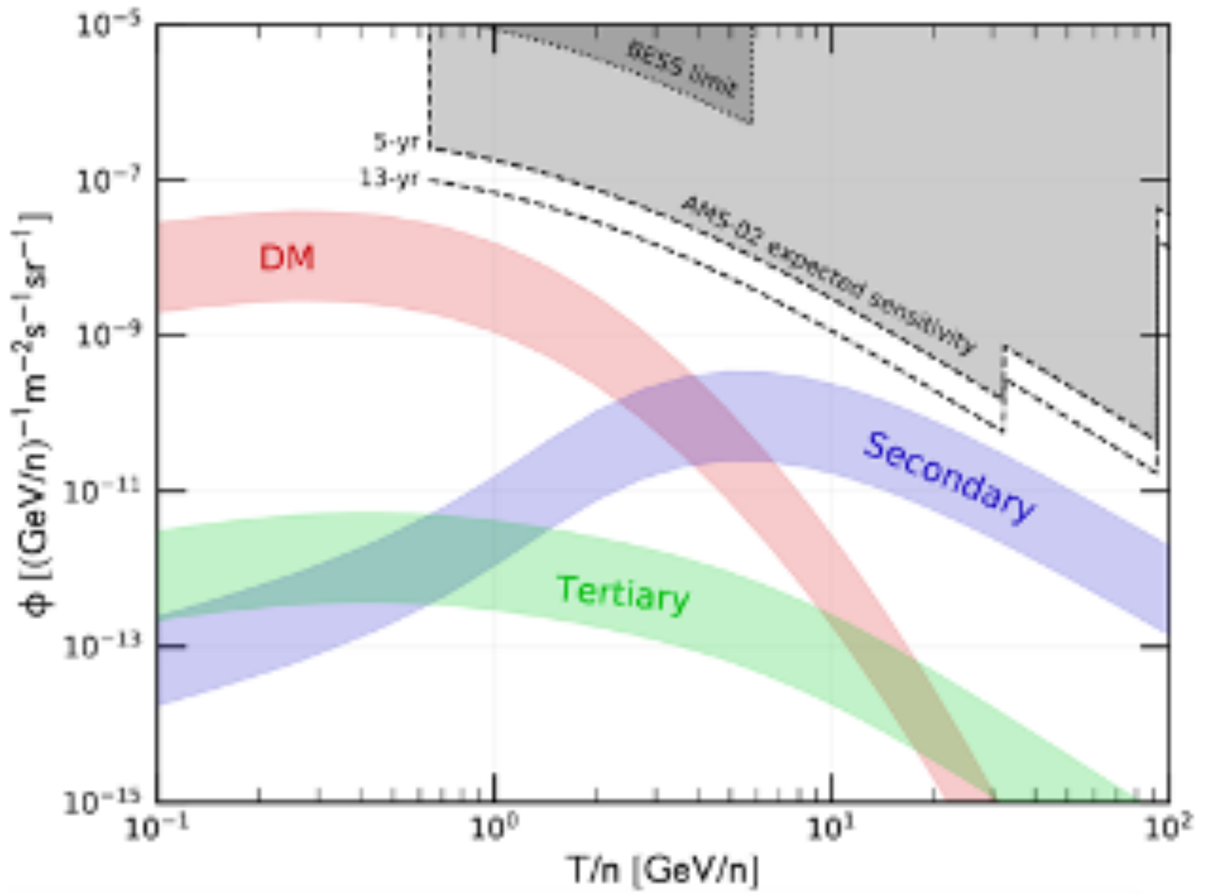




CMS-DP-2021-037



Antihelium flux

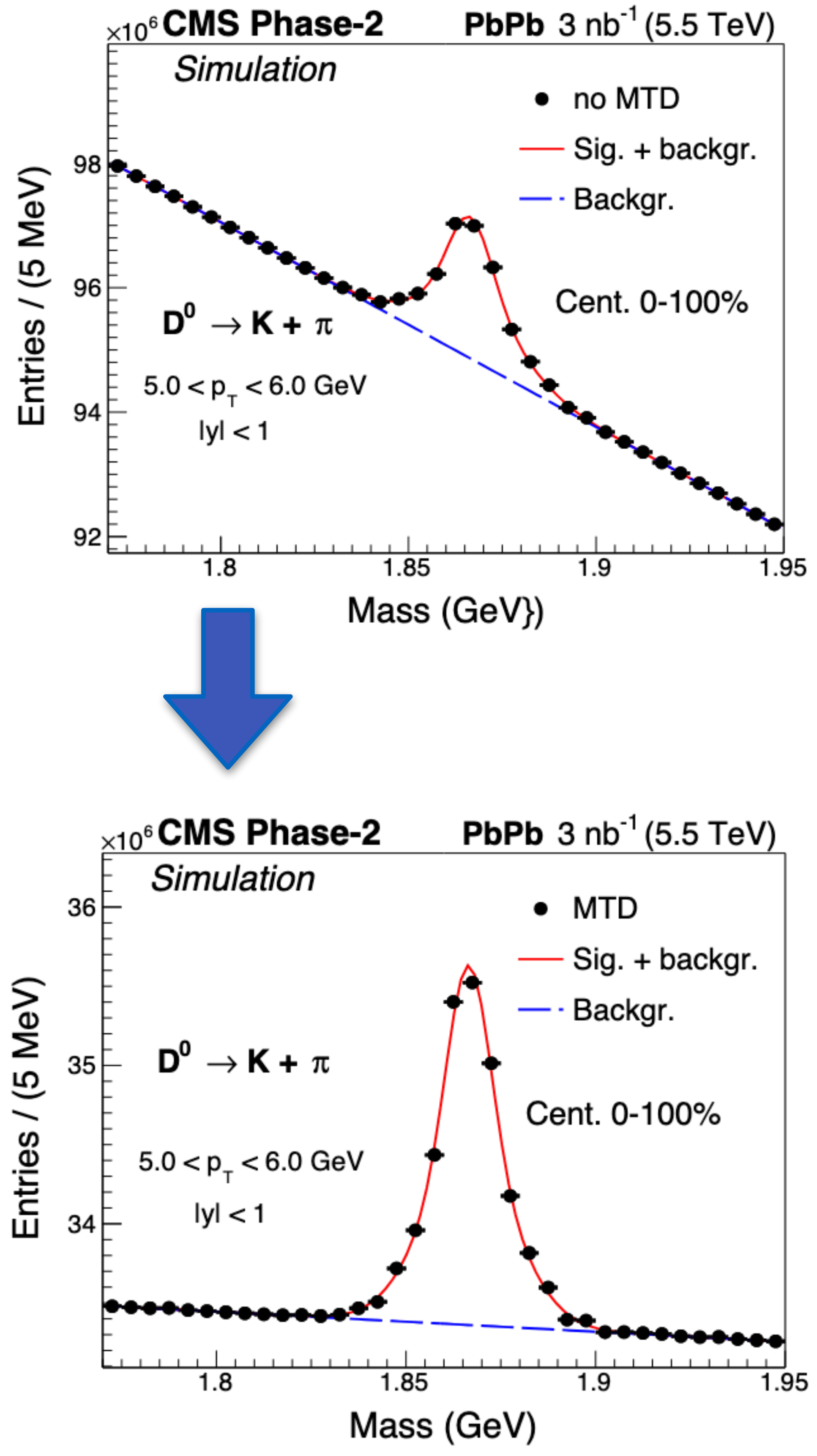


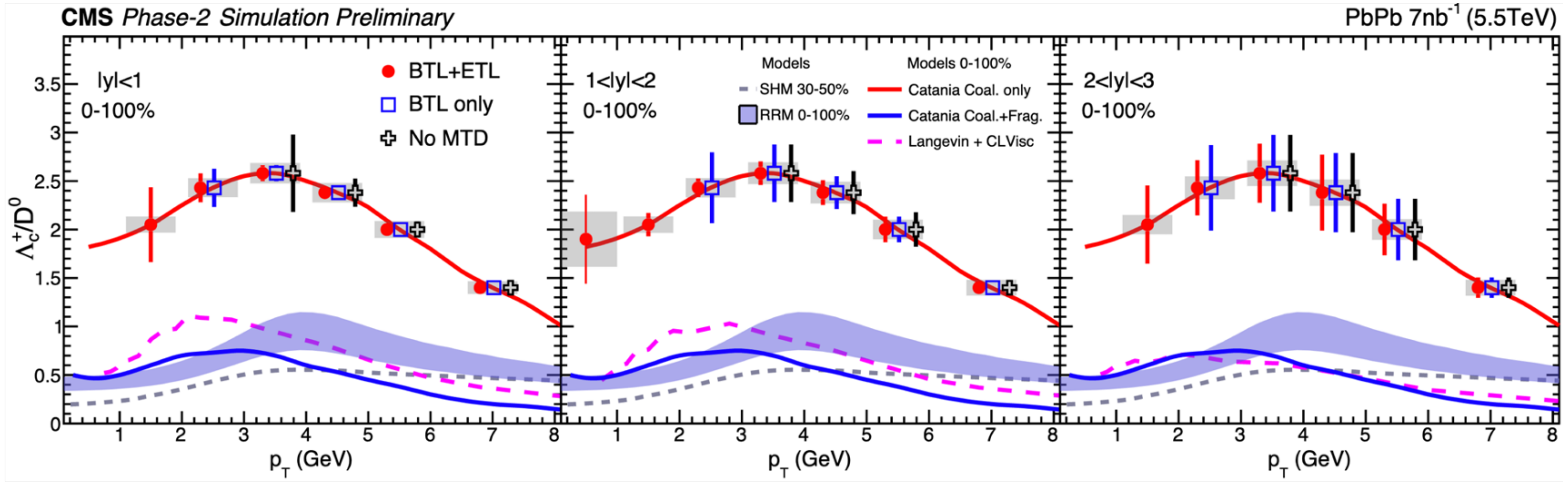
pp collisions: Light nuclei important input for dark matter searches

Korsmeier et al., PRD97 (2018) 103011

Charm measurements w/ PID

Charm hadronization measurements in heavy-ion collisions
→probe interaction of charm quarks recombining w/ light quarks in the quark-gluon plasma

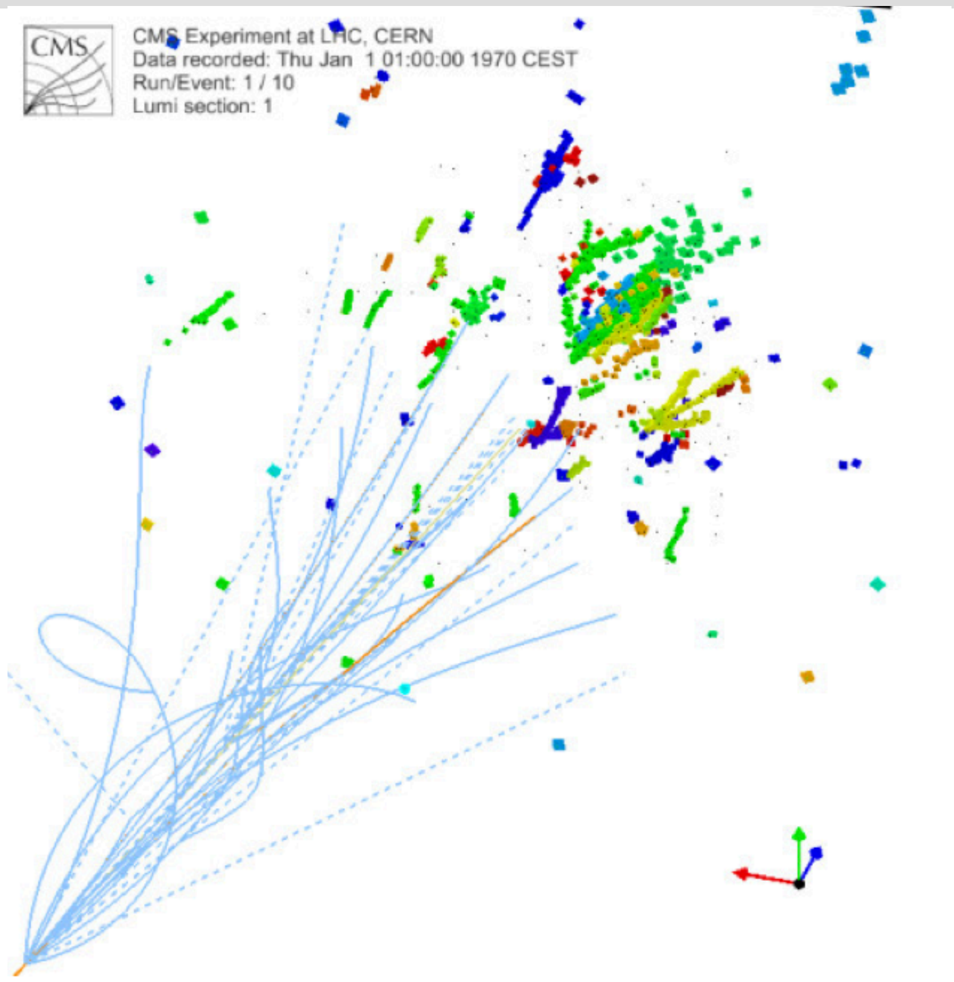




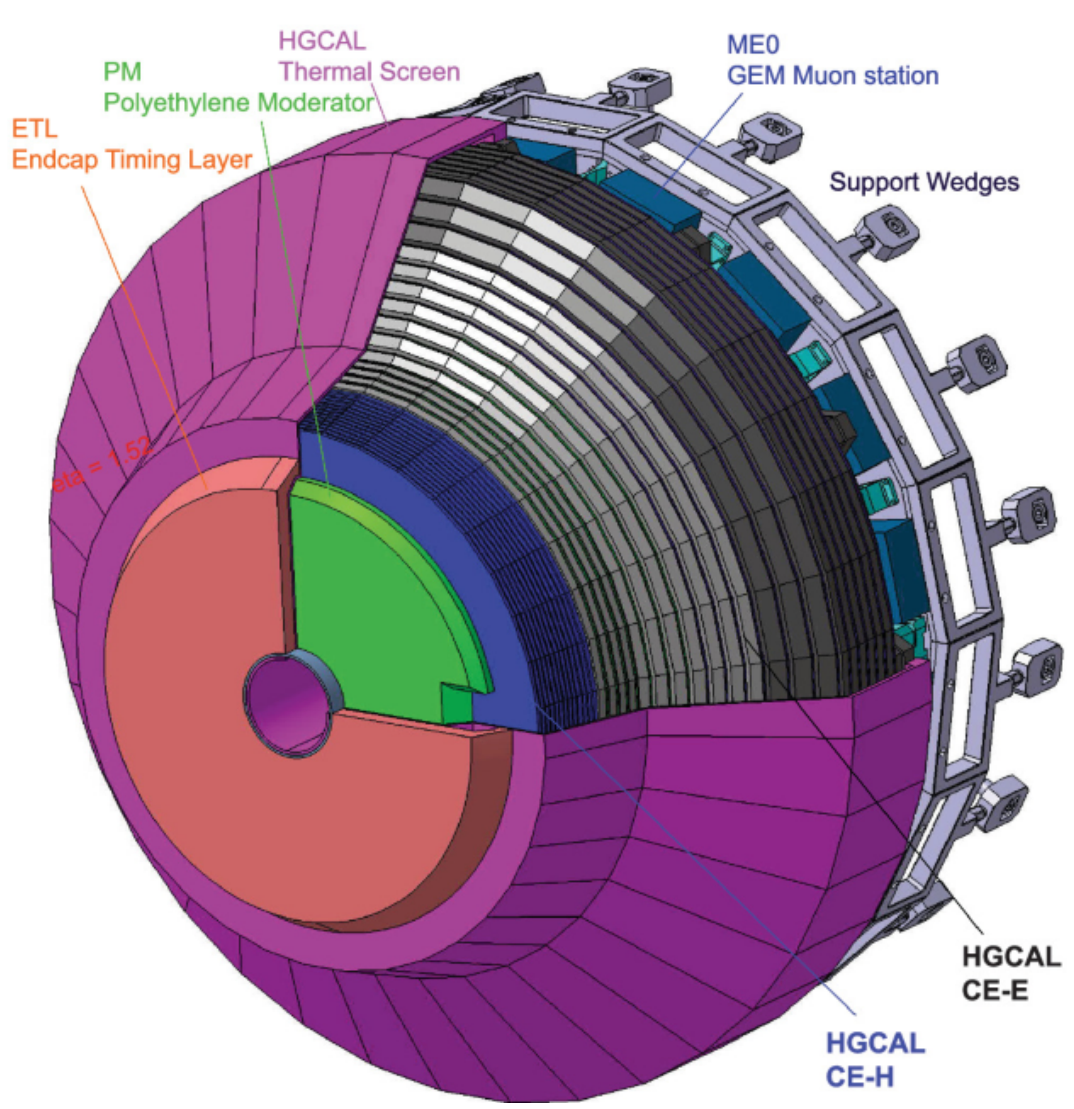
CMS-DP-2021-037

Charm and beauty hadron measurements over six units of pseudorapidity
Charmed hadrons down to $p_T = 0$ in η range not covered by other experiments

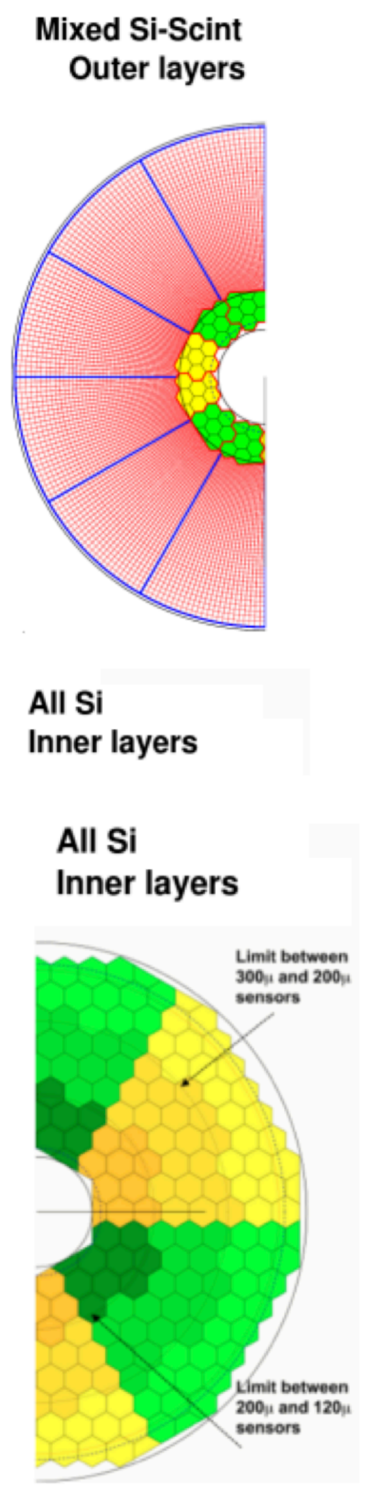
HGCAL: High granularity calorimeter



Current endcap calorimeters will not be able to withstand HL-LHC luminosity
Upgrade will be designed *particle flow*, i.e., emphasis on high granularity



Hadronic (CE-H)
- Mix of Si sensors & "SiPM-on-tile"
- Steel absorbers
- 21 layers
- 9.5 λ (incl. CE-E)

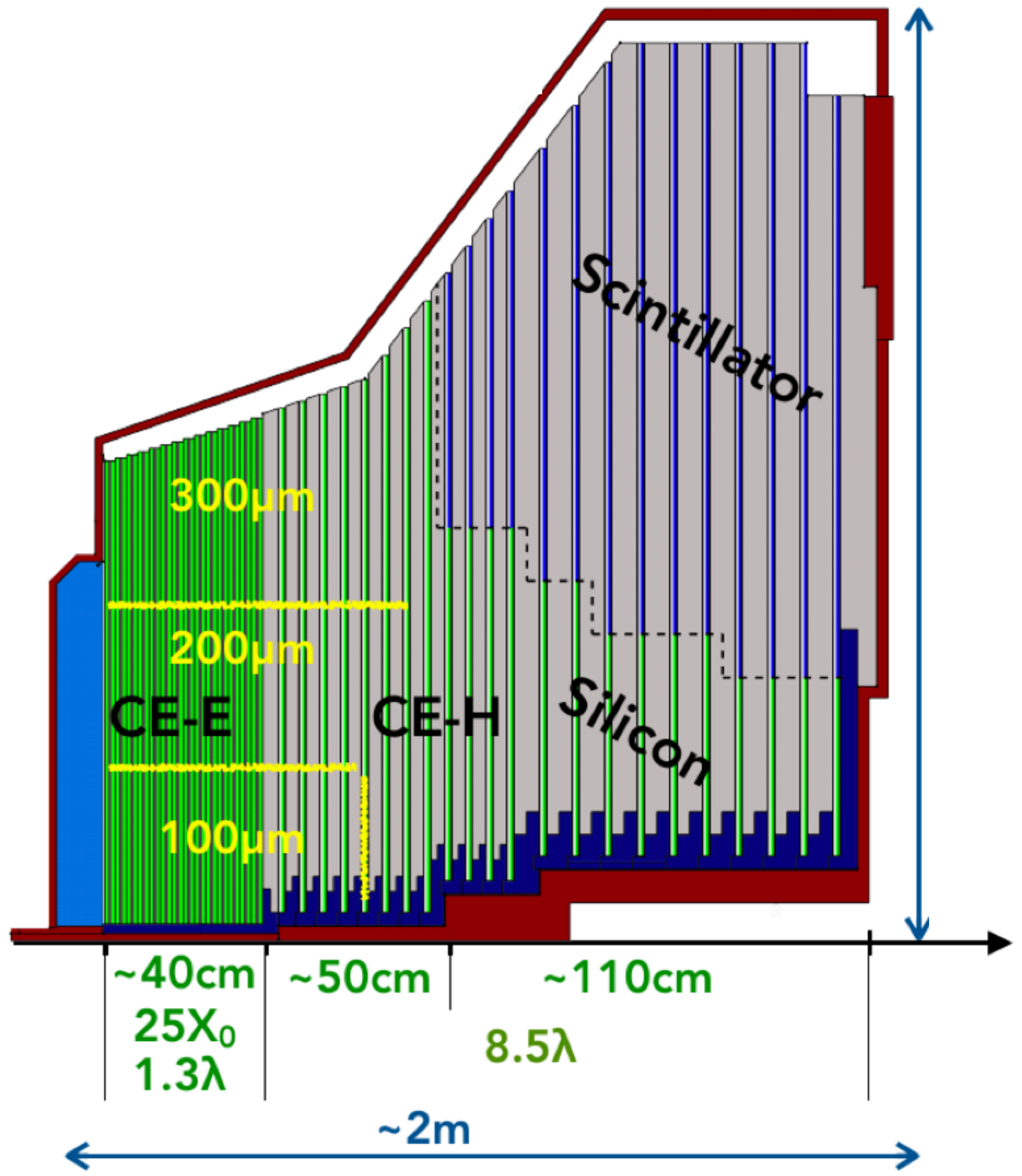


5D imaging calorimeter:

Fine transverse & longitudinal segmentation &
Excellent time resolution (30 ps for $p_T > 5$ GeV)
- Optimized contribution w/ other subdetectors
- Can measure from MIPs to TeV showers
- Good performance for highly boosted objects
- Removal of PU contributions from showers

- Acceptance: $1.5 < |\eta| < 3$
- 6M silicon channels: cell size 0.5-1.1 cm^2, 620 m^2
- 240k scintillating channels: tile size 4-30 cm^2, 400 m^2
- 215 tons for each endcap
- Full system at -30 C

Electromagnetic (CE-E)
- Silicon sensors
- Pb, Cu & CuW absorber
- 26 layers
- 25.5 X_0, 1.7 λ



NB: HGCROC ASIC design being re-used for EIC CALOROC(A)

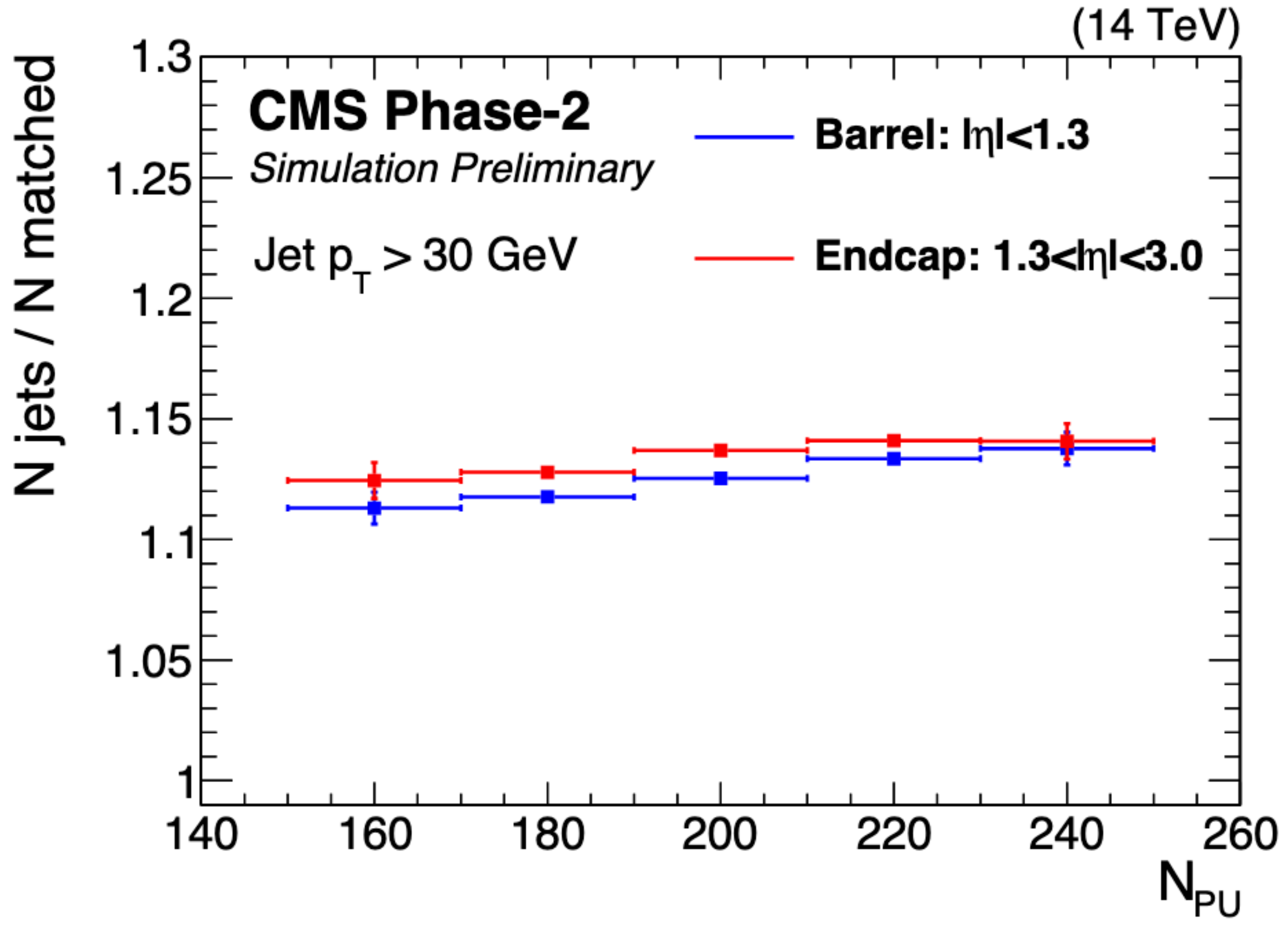
HGCAL performance

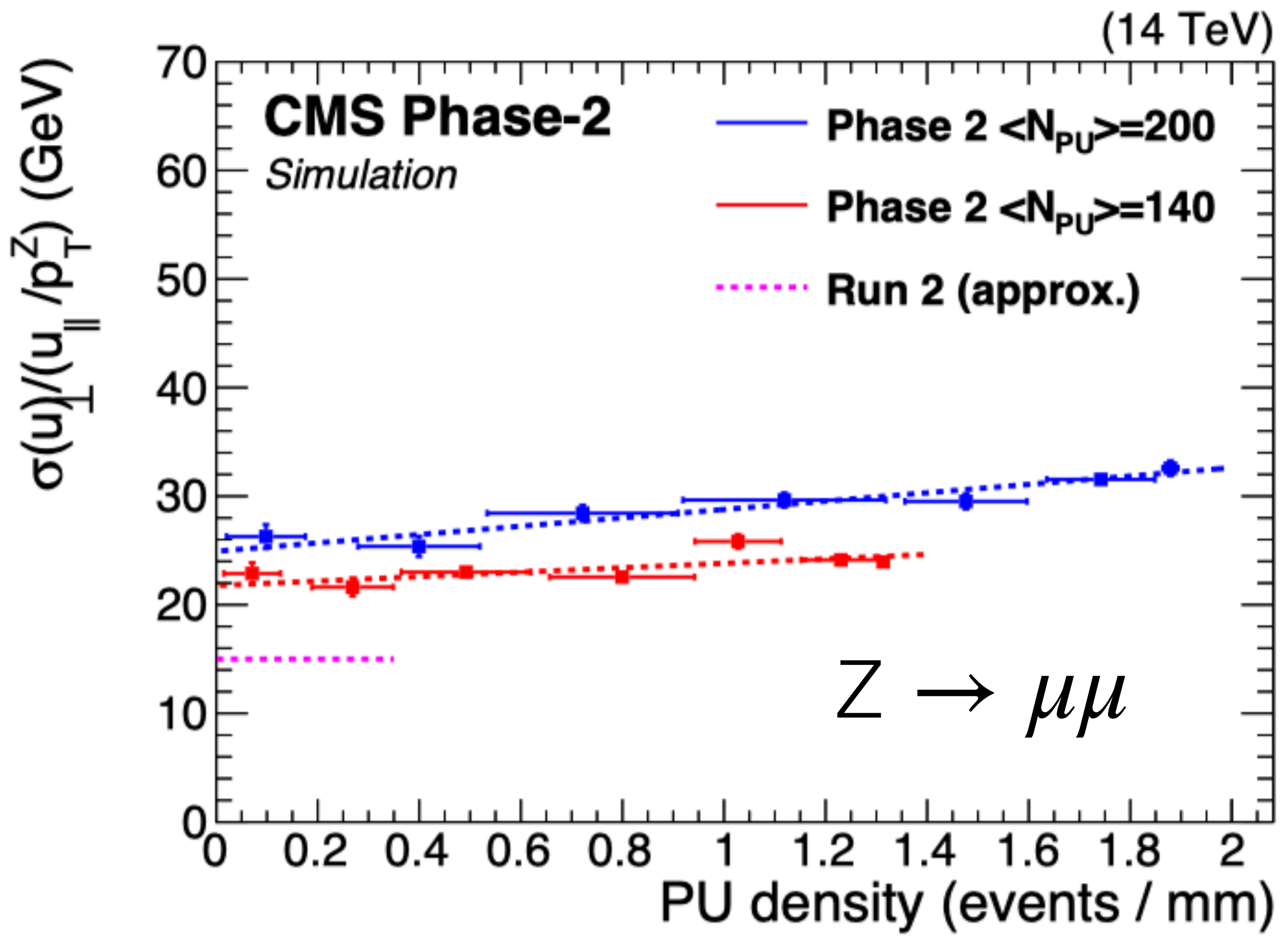
- Designed to maintain current physics performance with much higher pile-up
- Comparable performance to barrel calorimeter system, not currently the case

$100 < \text{jet } p_T < 200$ GeV

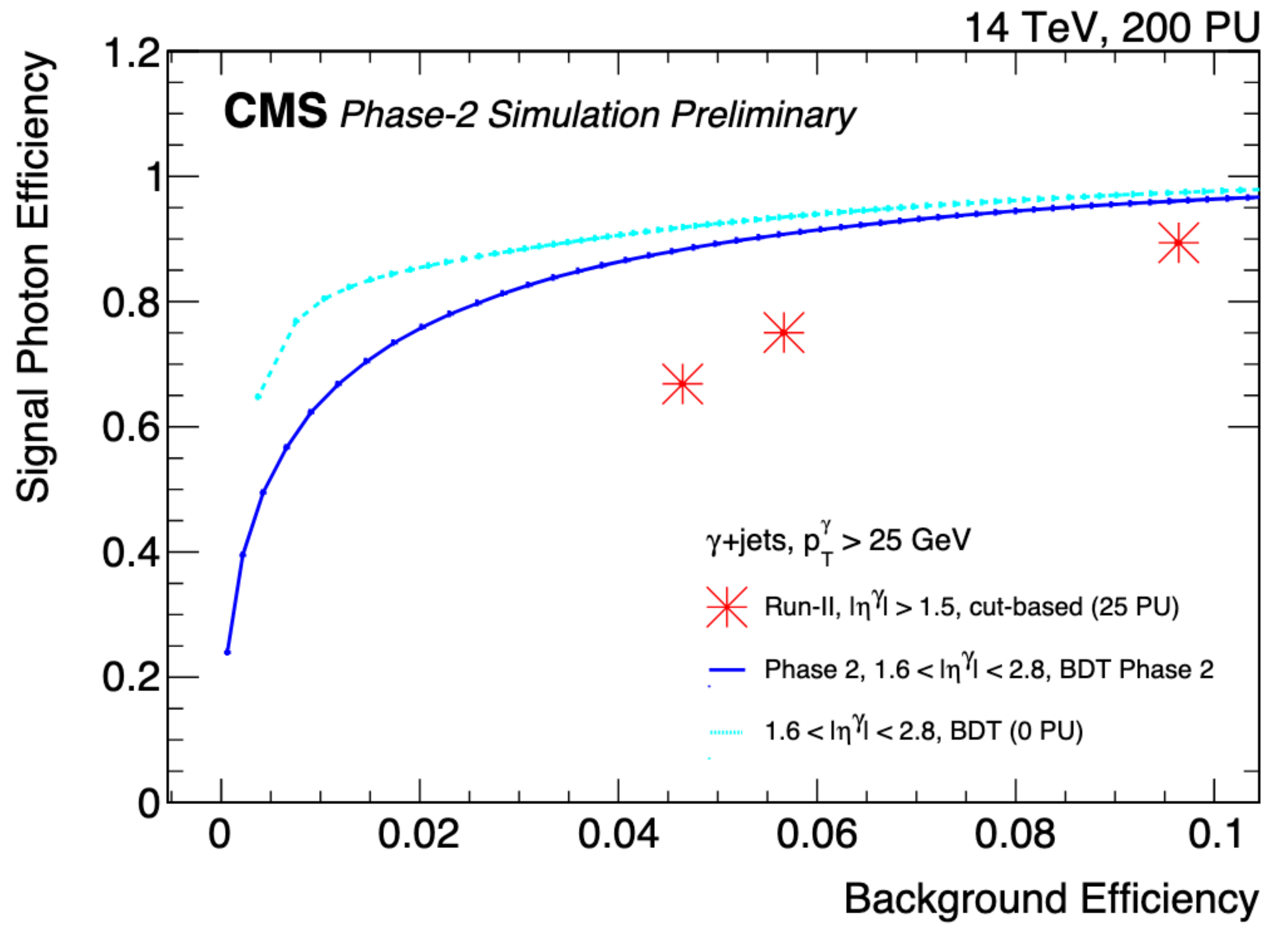
Scenario	Softdrop jet mass resolution
Barrel calorimeter, Phase-0, PU=25	7.4%
Barrel calorimeter, Phase-2, PU=0	7.5%
Barrel calorimeter, Phase-2, PU=200	10%
Endcap calorimeter, Phase-0, PU=25	8.0%
Endcap calorimeter, Phase-2, PU=0	7.5%
Endcap calorimeter, Phase-2, PU=200	11%

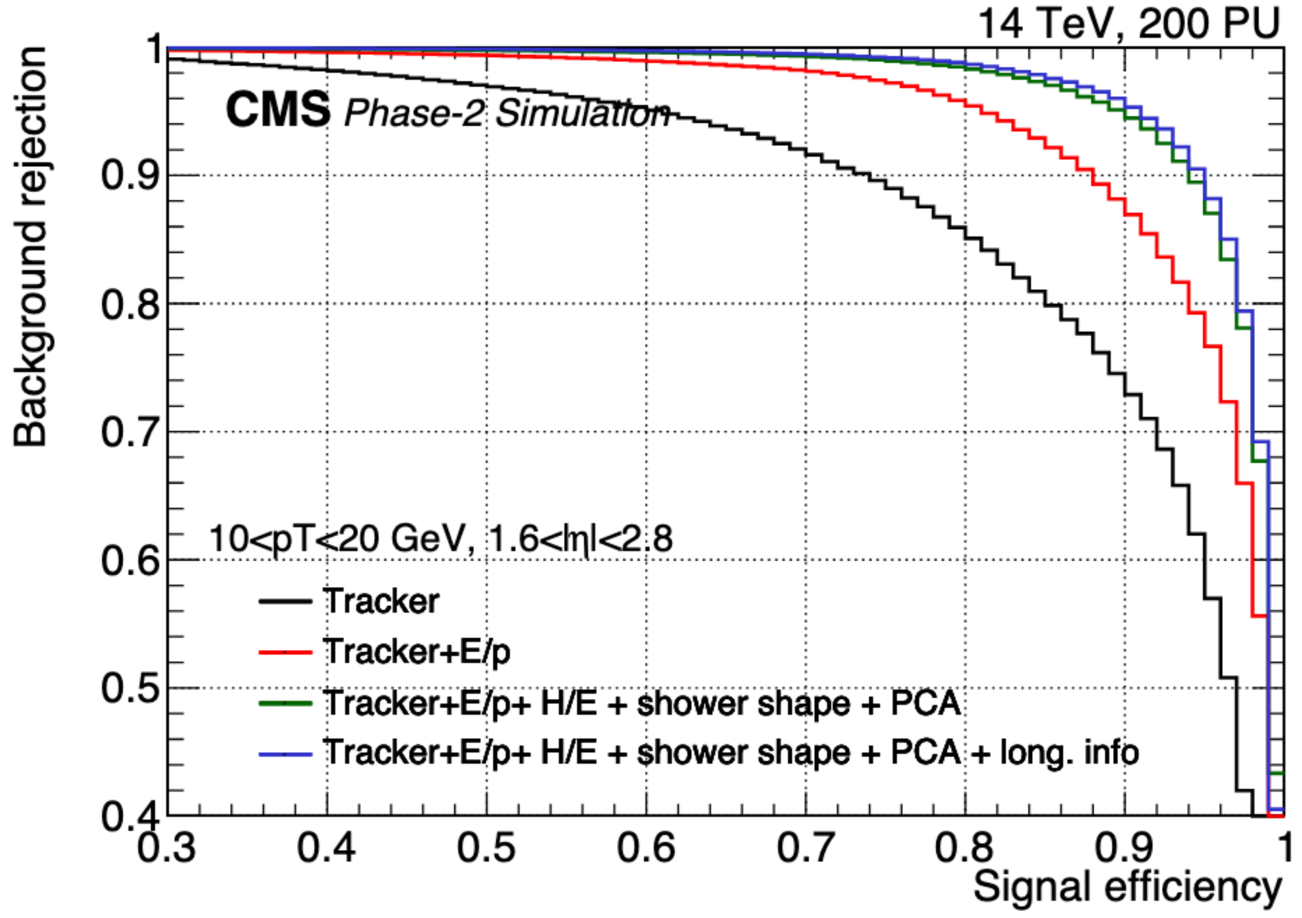
Jets & Missing E_T



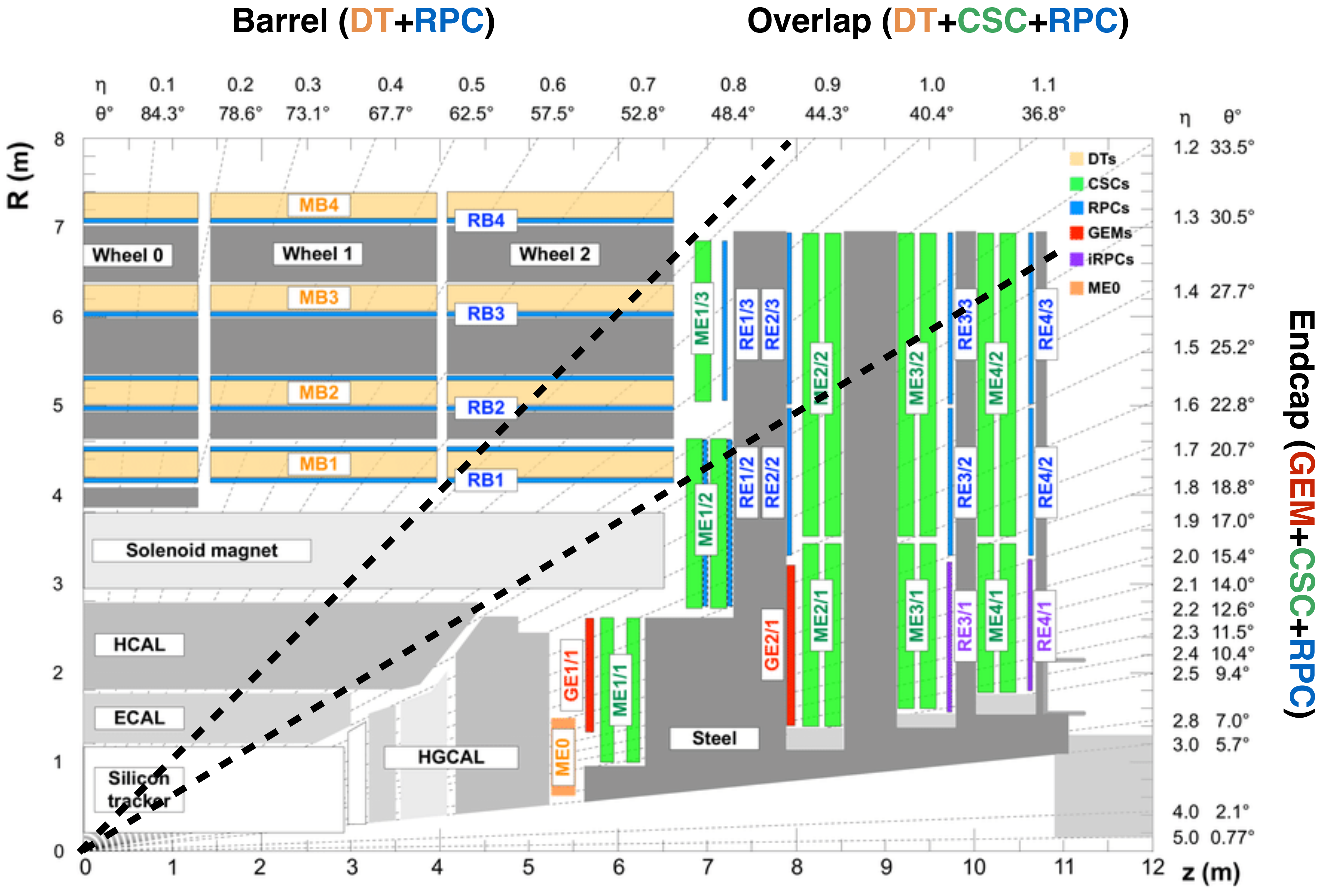


Photons & electrons





Muon system upgrades



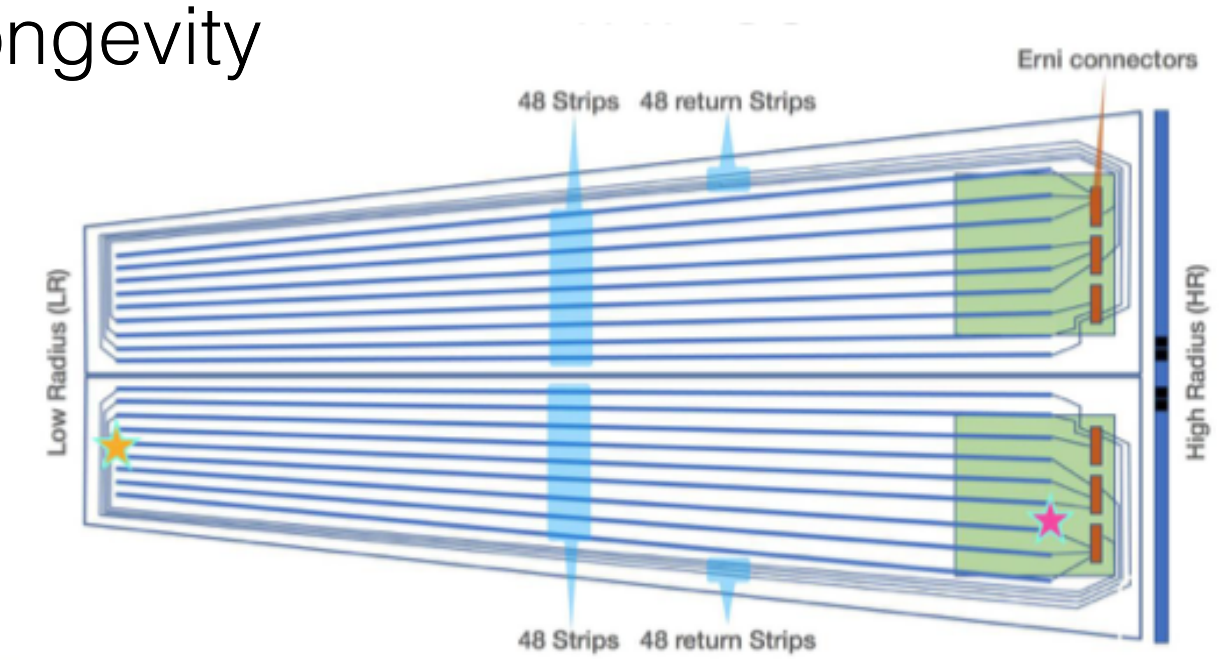
Goals:

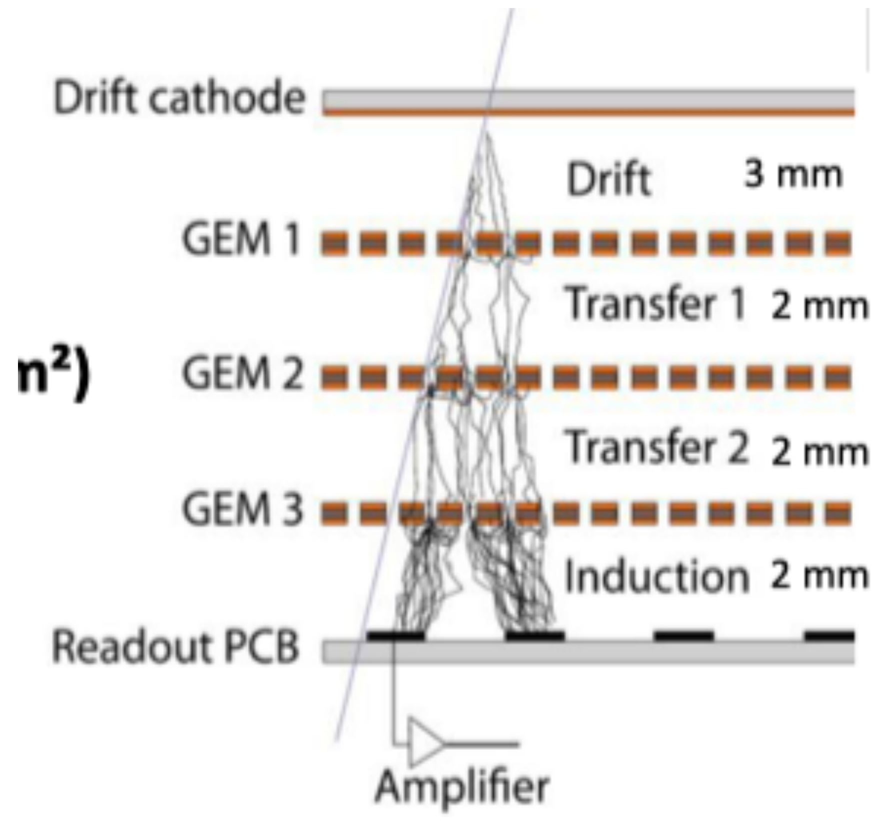
- Upgrade electronic of existing detectors (DT, CSC, RPC)
- Reinforce & add redundancy in forward region: $|\eta| > 1.7$
- Extend muon ID & trigger coverage to $2.4 < |\eta| < 2.8$

Improved Resistive Plate Chambers (iRPC)

Two new stations in $1.8 < |\eta| < 2.5$

- better rate capability, timing & longevity





New Gaseous Electron Multipliers (GEM)

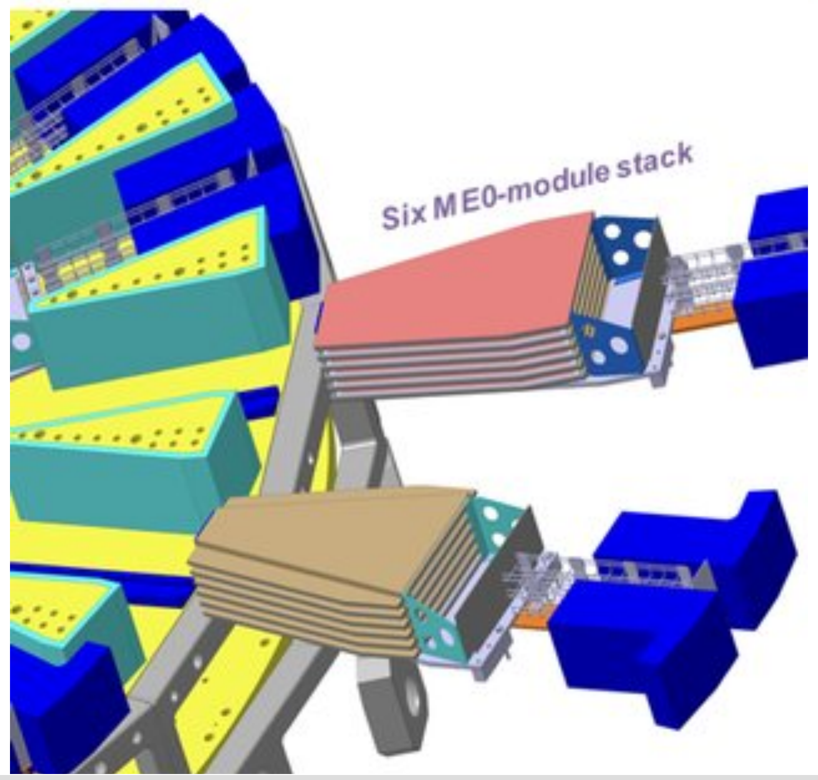
GE1/1, GE2/1: triple GEM stacks

- add redundancy to CSCs
- improve reconstruction & trigger at large η

✓partially installed for already in Run 3

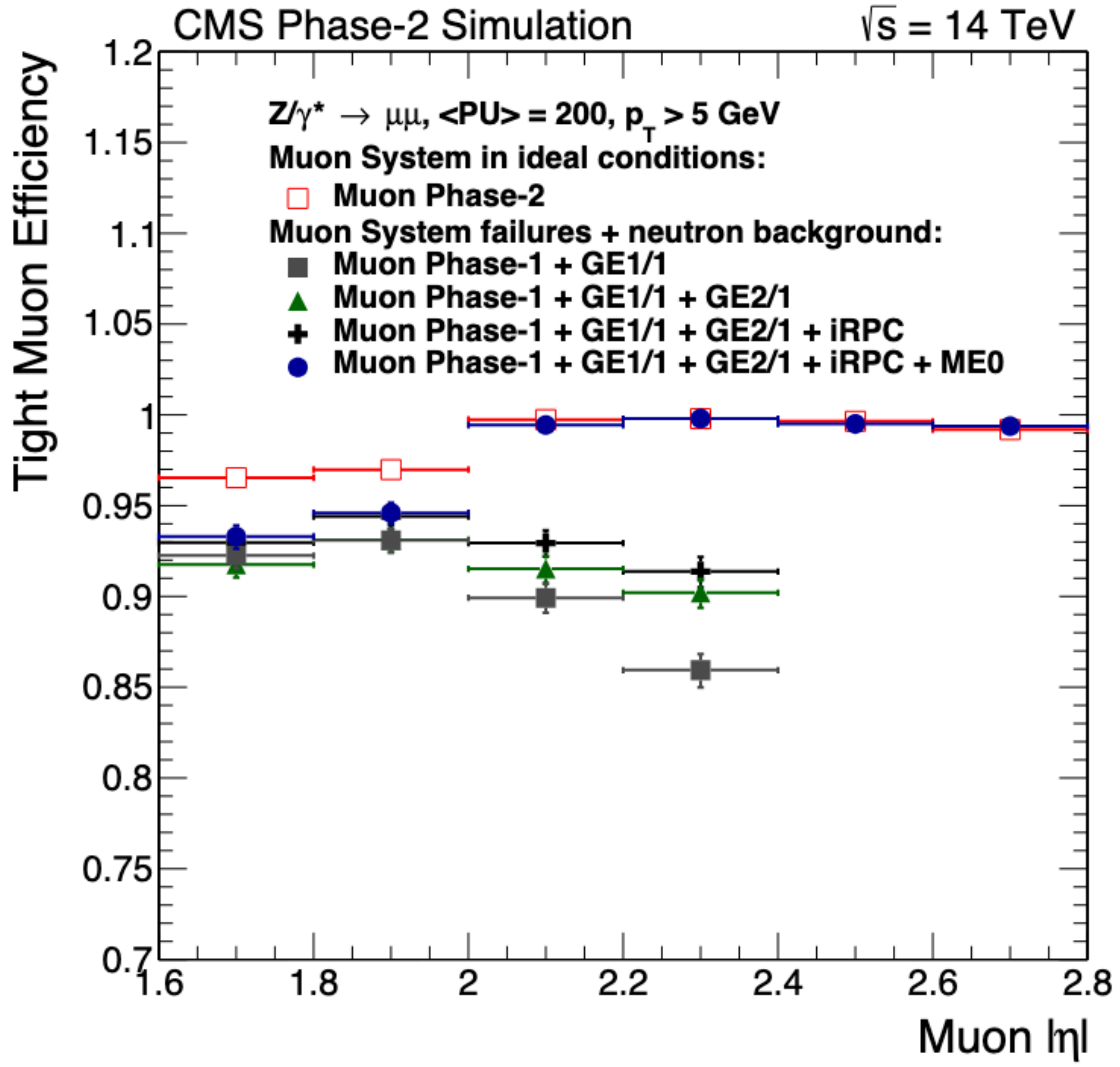
ME0: 6 layers behind HGCAL

- extend coverage to $|\eta| < 2.8$

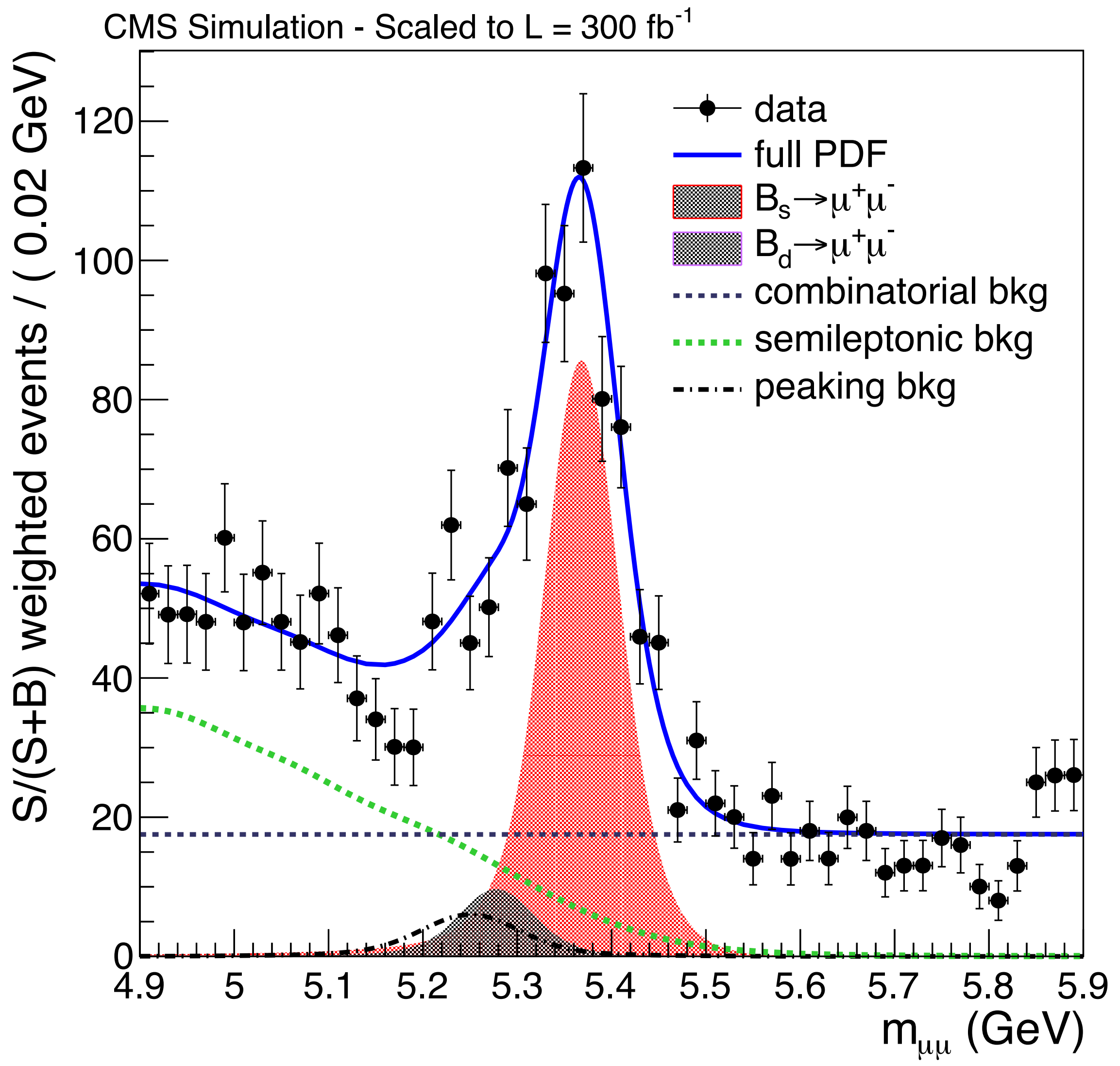


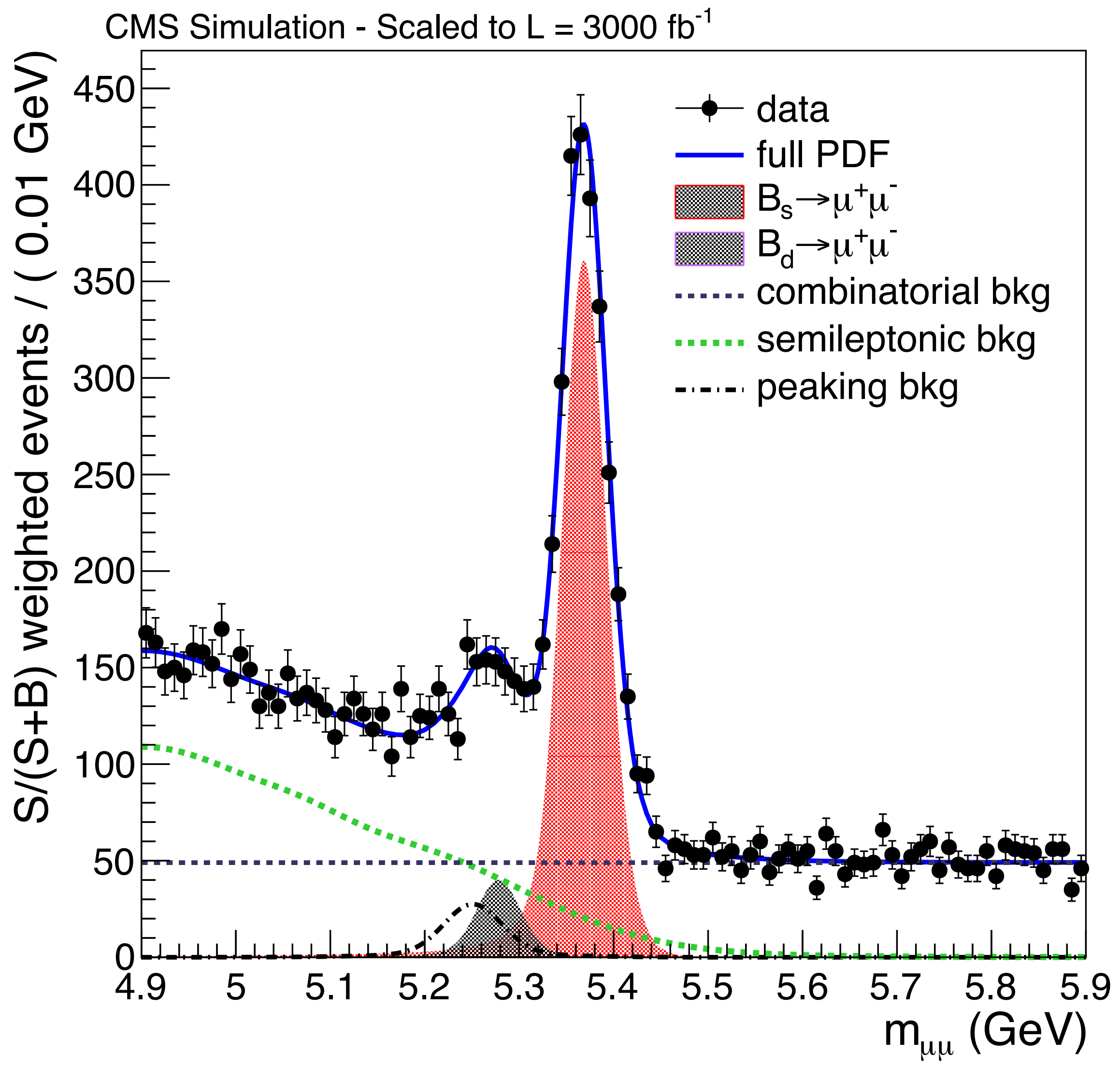
Muon performance

Extended coverage at large η



Improved mass resolution with upgraded tracker





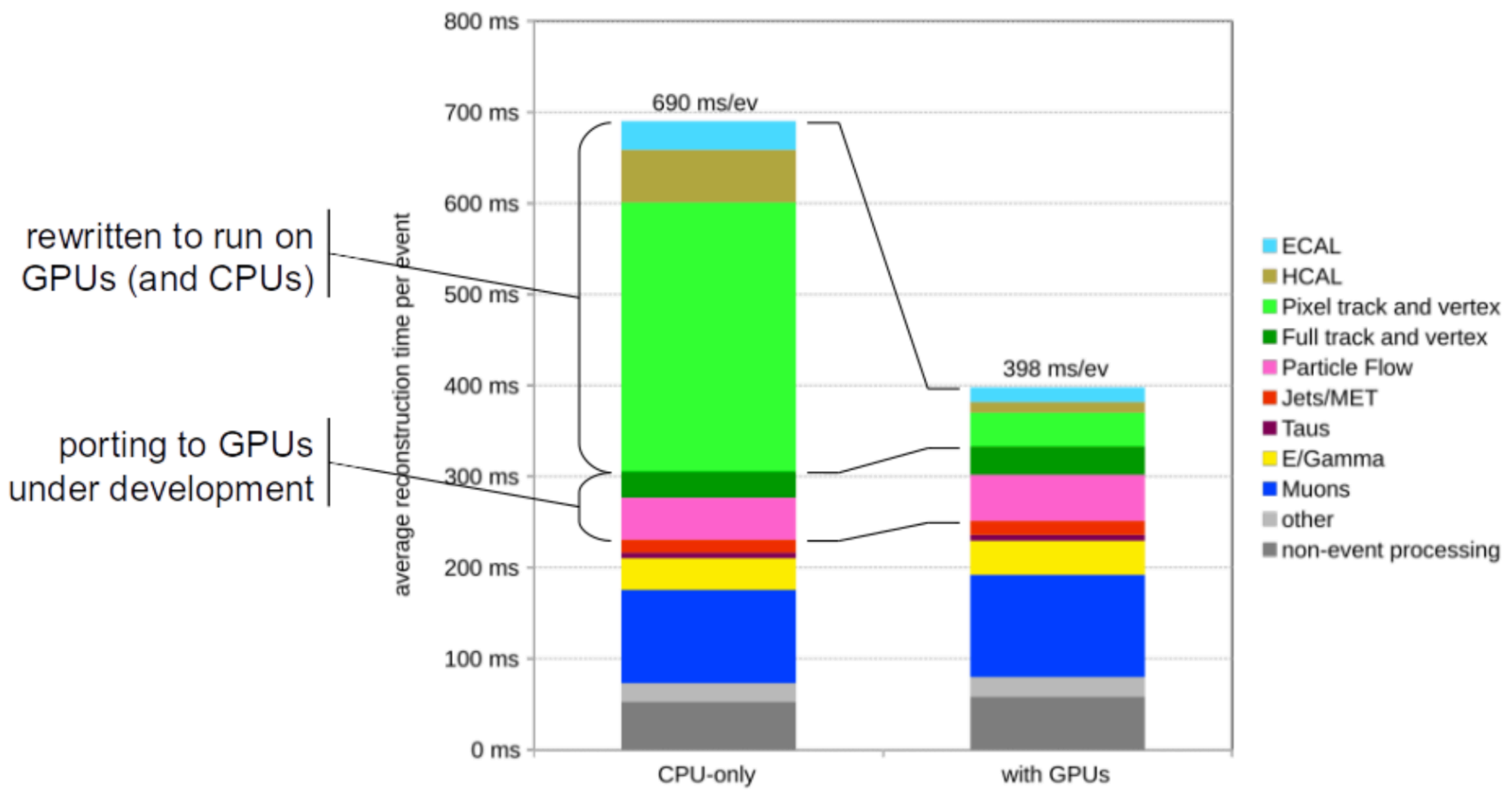
Particularly valuable for low mass resonances, e.g., J/ψ to $p_T = 0$

Particularly useful for adjacent resonances, e.g., Υ(2S) & Υ(3S)

To be explored: Improved muon ID using HGCAL to veto hadrons

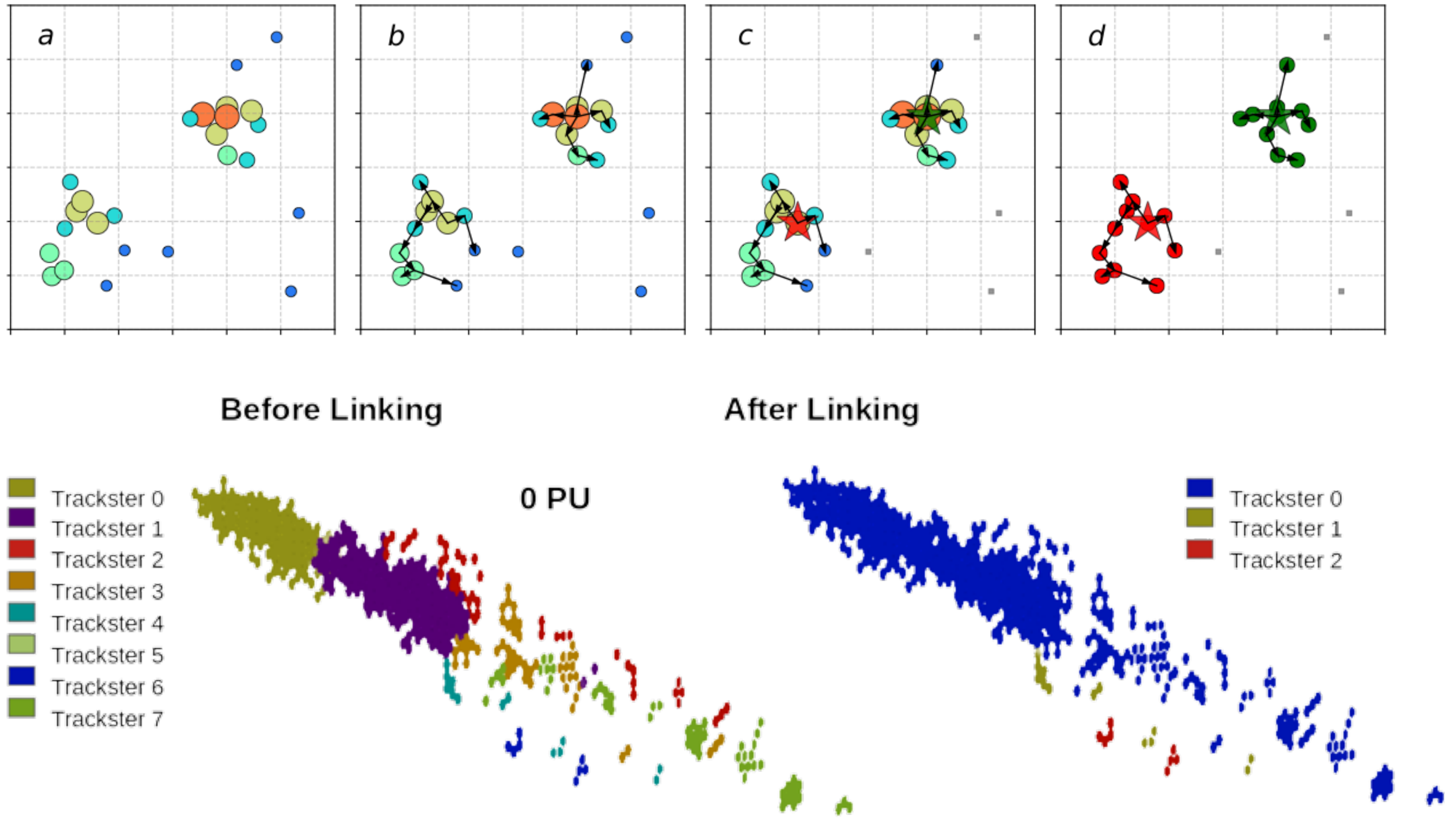
Phase-2 reconstruction algorithms

In Run 2 GPUs were deployed at HLT to accelerate reconstruction
GPUs increasingly available at sites used opportunistically
Phase-2 algorithms being designed for heterogeneous processing



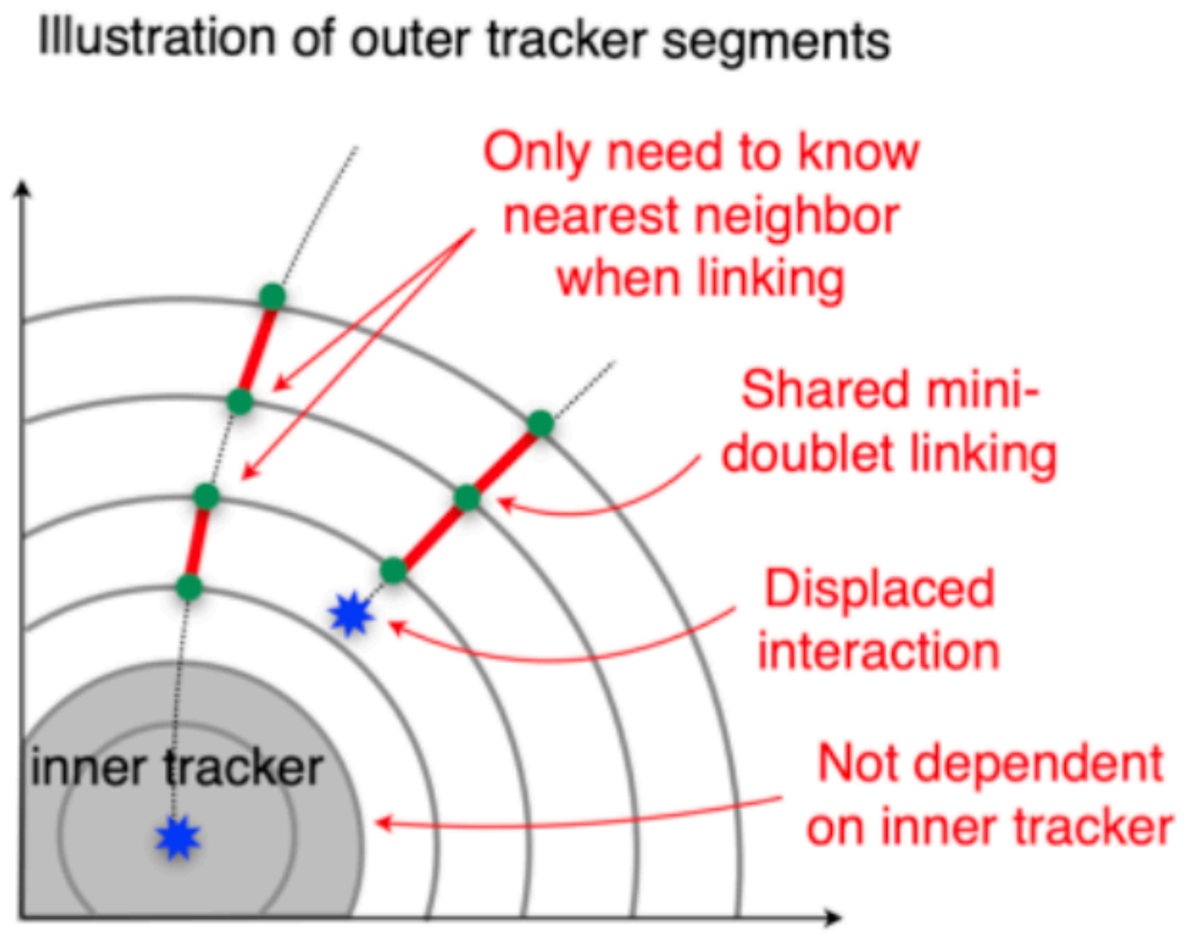
HGCAL: CLUE / TICL

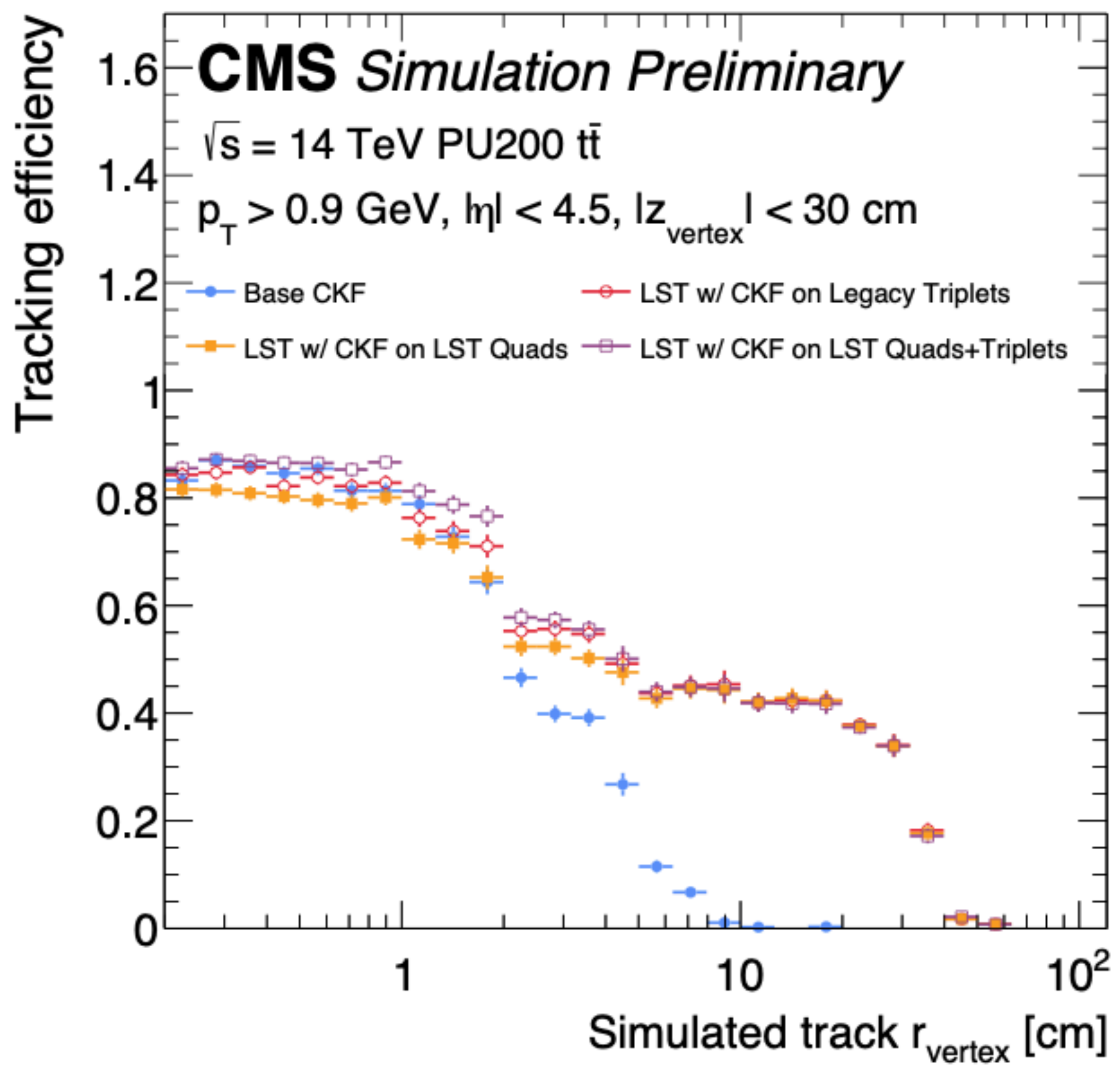
arXiv:2001.09761



Tracker: Line Segment Tracking

CMS-DP-2024-014
arXiv:2407.18231



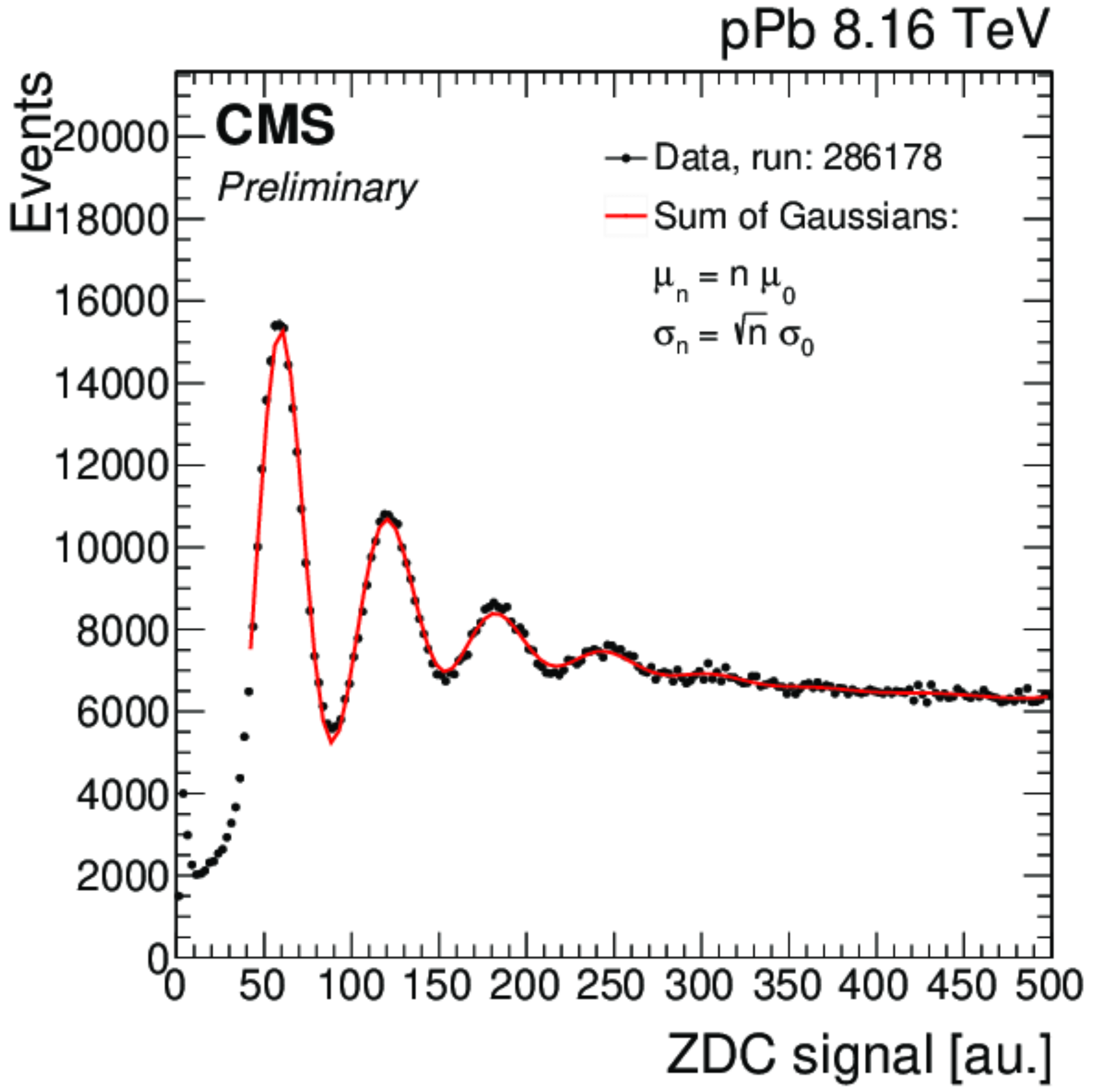


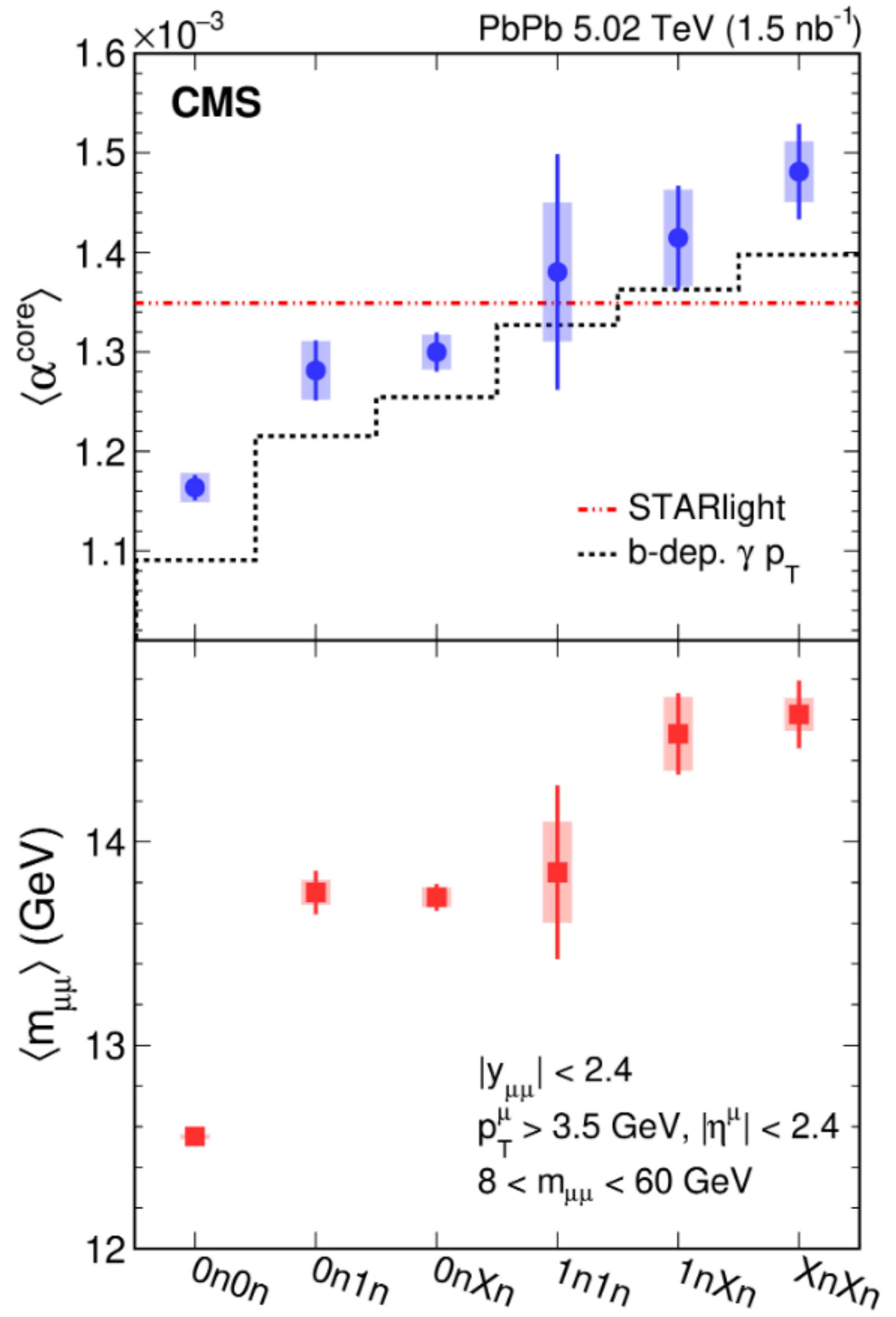
CMS software makes use of the alpaka portability framework to run on different architectures

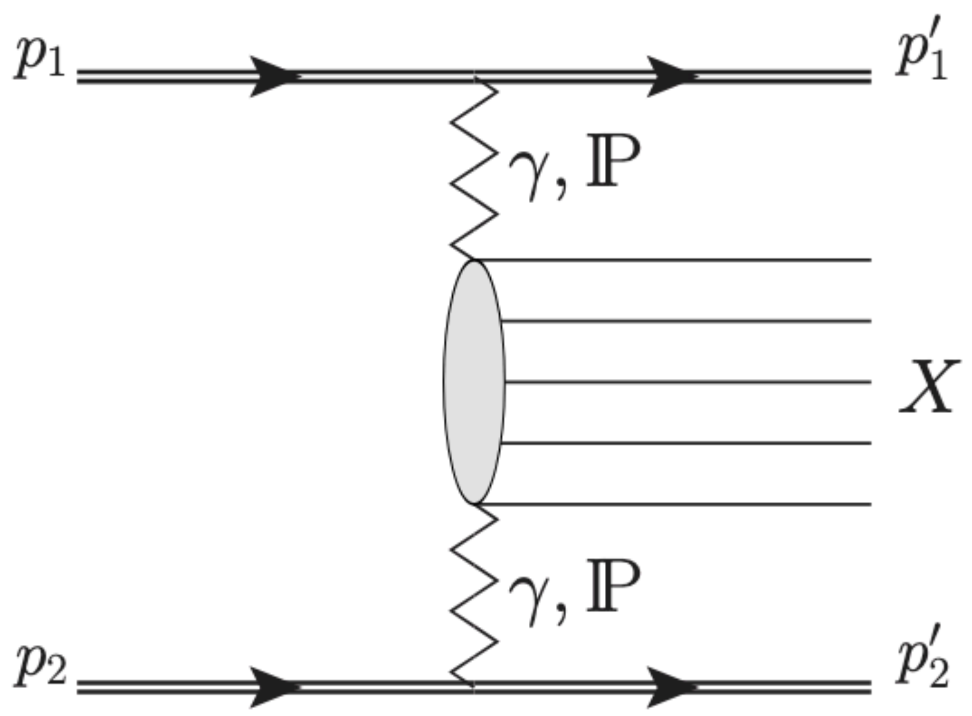
Forward detector upgrades

Zero Degree Calorimeters (ZDC): essential component for heavy-ions

- Key component of minimum bias trigger for hadronic interactions
- Used to disentangle different electromagnetic process (UPC)

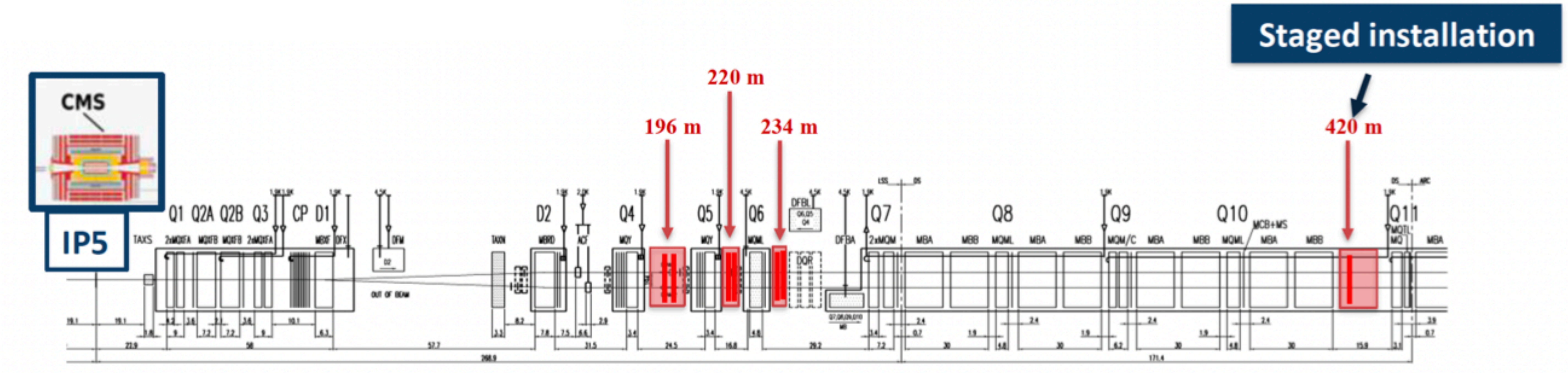






Central Exclusive Production (CEP)

Proton Spectrometer (PPS) detects deflected protons



Rad-hard ZDC to be deployed for HL-LHC
Joint ATLAS & CMS development

CMS-TDR-024

Legacy system measured $3 < \Delta p/p < 15\%$
Run 4: $1.42 < \Delta p/p < 20\%$
Run 5: $0.33 < \Delta p/p < 20\%$

EOI: CMS NOTE-2020/008

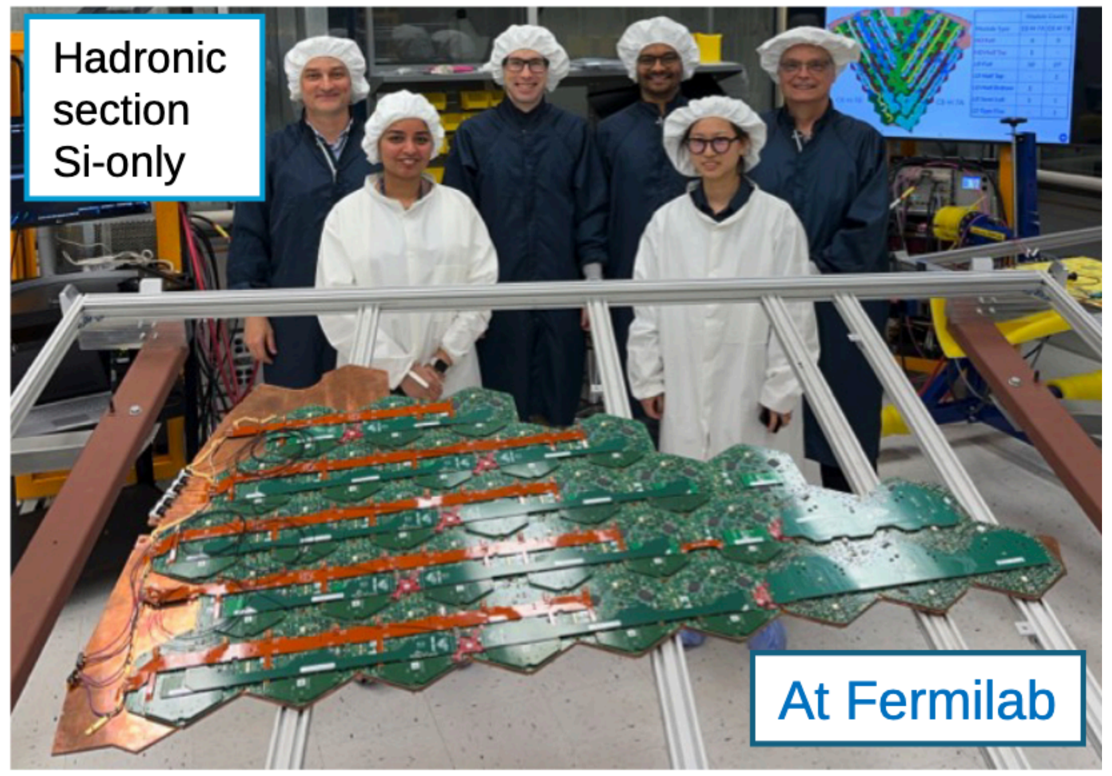
Upgrade status as of Sept. LHCC

On track! **designs (almost) all completed** **– many things to do, surprises still possible**

- module production of Inner and Outer Tracker, HGCAL and MTD ongoing
- DAQ, Barrel Calorimeter: production ongoing
- Muons: RPC (100% done, 50% installed) and CSC almost done, DT (60%) and ME0 (7/36 stacks)
- Barrel Timing Layer: >90% sensor modules, 60% readout modules, 10% trays done
- Endcap Timing Layer: sensors and ASIC in procurement, next electronics and mechanics
- Outer Tracker: >15% hybrids, 428/8000 2S and 114/6000 PS modules done – 2nd ladder
- Inner Tracker: sensors 78% quads, 55% duals, 55% 3Ds received sensors, some hiccups in hybridization
  - all module types in pre-production
- HGCAL: ~300 Si modules built, tile-module production started, evaluating pre-series cassettes
  - 63% molded and 42% machined cast tiles, 100% Si sensors and 100% SiPMs, board production going

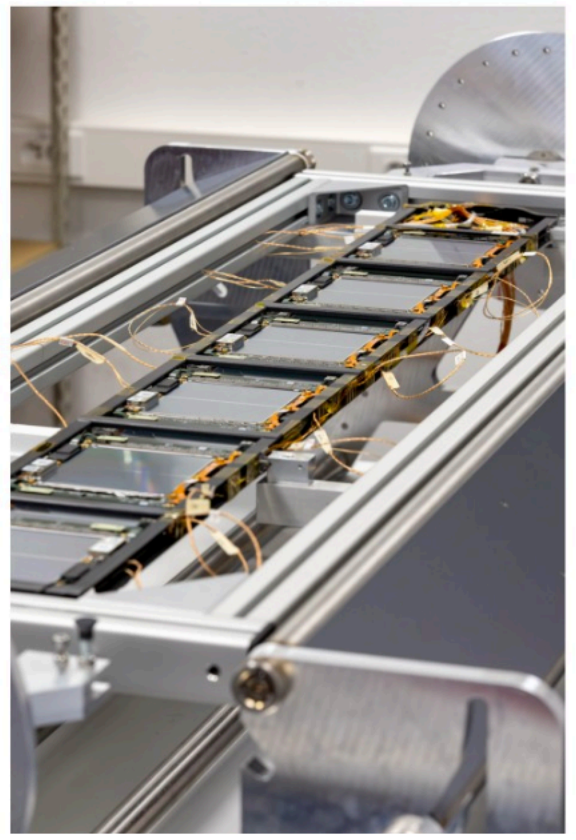
2025 objective:
all designs finalised, tracker module & ladder, HGCAL module & cassette production started

HGCAL pre-series cassettes



Outer Tracker progress

- so far so good!
- 2nd ladder (out of 372) being assembled



Photographer : Nicolas Busser, IPHC

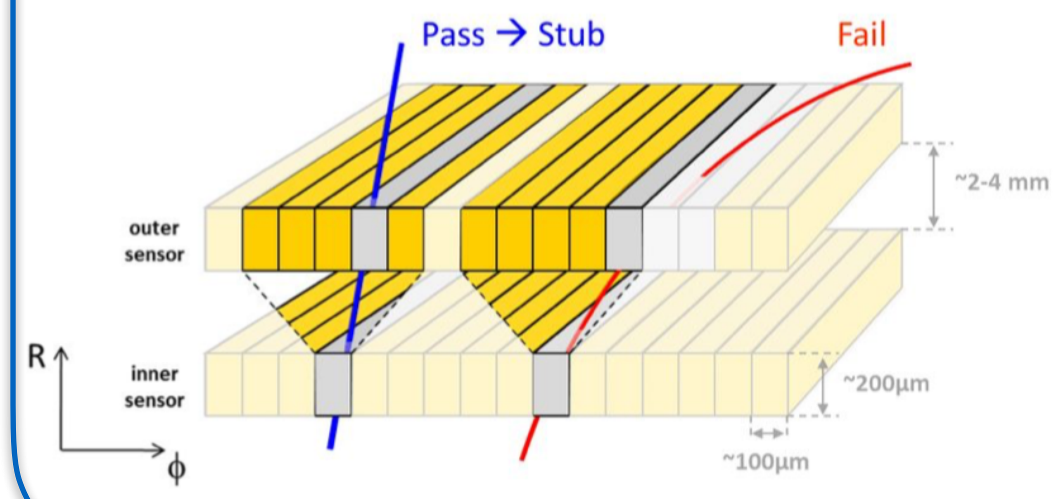
First HGCAL absorber

- fully assembled, swivel tested & packaged

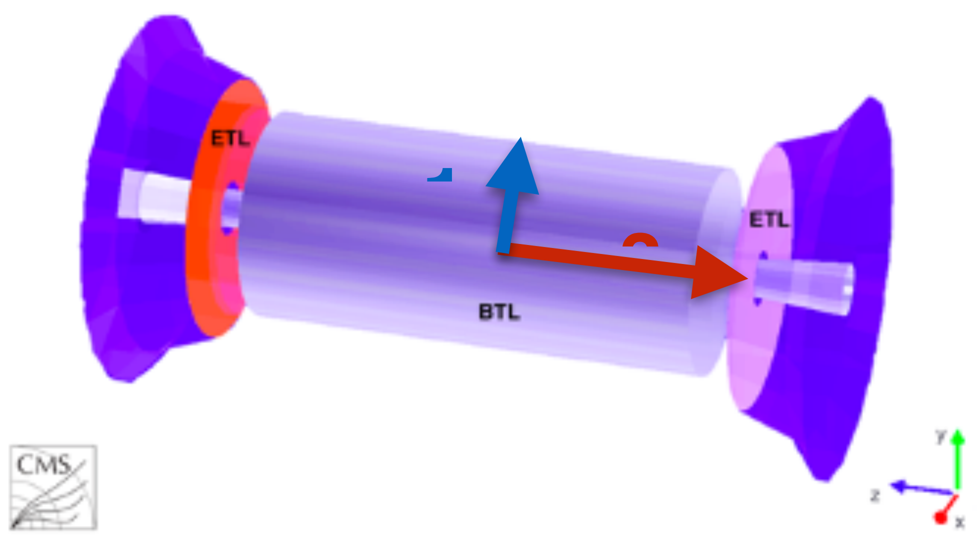
To conclude

Starting next year CMS will undergo a series of major upgrades for the HL-LHC era, including:

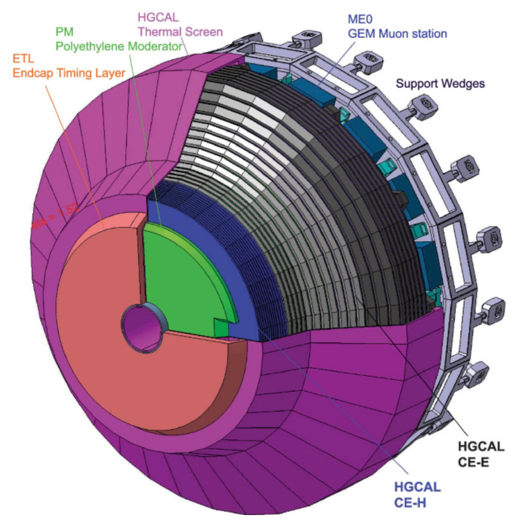
A new tracking system



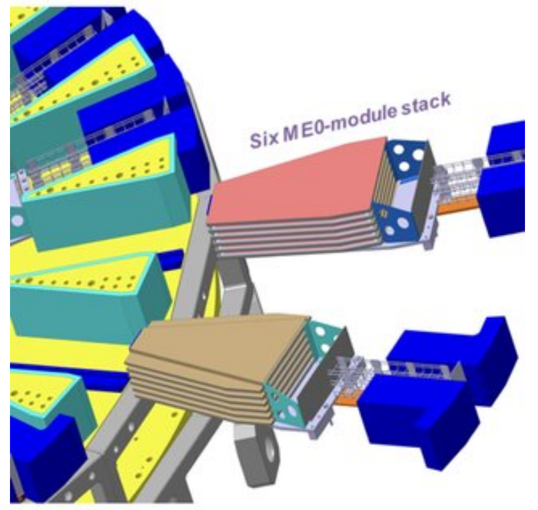
the addition of timing layers



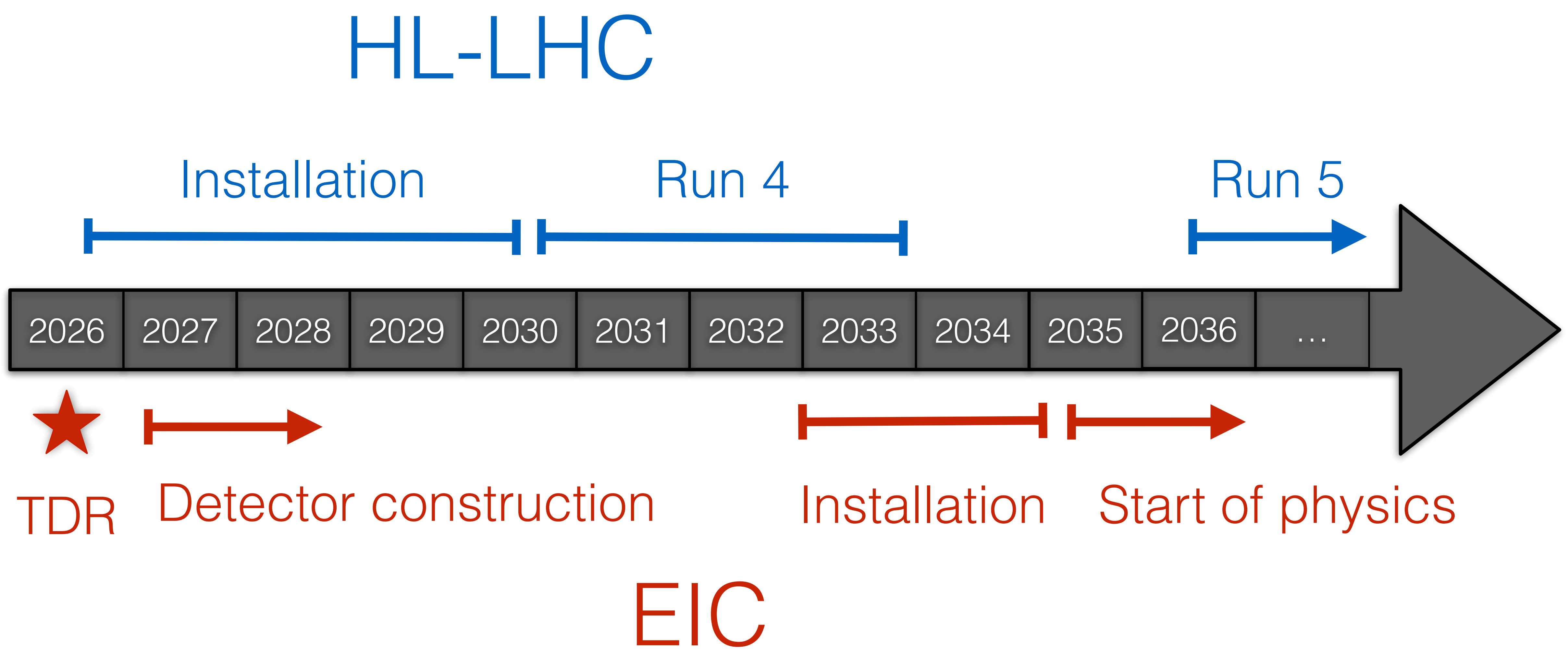
a high granularity calo endcap



extended muon coverage



… and much more



Concurrent program at HL-LHC and EIC provides excellent opportunities for synergies